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TITLE (6) ROCKET ENGINES - LIQUID PROPELLANT.
VOLUME I - SMALL ENGINES,

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VOLUME I - SMALL ENGINES.

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ABSTRACT

This document contains information on rocket engines using propellants stored as liquids or gases.

Volume I contains information on engines used for reaction control systems and low velocity increment propulsion systems. Cold (ambient) gas, heated gas, monopropellant and bipropellant engines are considered. Estimates are made of performance, size and power requirements. Operating principles, hardware details and systems consideration are discussed.

Volume II has data on engines with thrusts of 100 pounds and larger.

KEY WORDS

| | |
|-------------------|--------------------------|
| Bipropellant | Reaction Control Systems |
| Cold Gas | Thrusters |
| Hot Gas | Resistojets |
| Monopropellant | Radioisotope Thrusters |
| Propulsion System | Rocket Engine |

VOLUME I
TABLE OF CONTENTS

| | <u>PAGE</u> |
|---|-------------|
| ABSTRACT AND KEY WORD LIST | 2 |
| TABLE OF CONTENTS | 3 |
| LIST OF FIGURES | 4 |
| LIST OF TABLES | 7 |
| 1.0 NOMENCLATURE | 8 |
| 2.0 SUMMARY | 11 |
| 3.0 INTRODUCTION | 12 |
| 4.0 MISSION REQUIREMENTS | 17 |
| 4.1 VELOCITY CONTROL | 17 |
| 4.2 REACTION CONTROL | 19 |
| 4.3 APPLICATIONS OF LOW ΔV THRUSTORS | 21 |
| 5.0 ROCKET ENGINE PERFORMANCE | 33 |
| 5.1 THEORETICAL STEADY STATE PERFORMANCE | 33 |
| 5.2 DELIVERED STEADY STATE PERFORMANCE | 38 |
| 5.3 TRANSIENT PERFORMANCE | 45 |
| 6.0 THRUSTORS FOR LOW ΔV APPLICATIONS | 47 |
| 6.1 COLD GAS THRUSTORS | 47 |
| 6.2 HEATED GAS THRUSTORS | 61 |
| 6.3 MONOPROPELLANT THRUSTORS | 78 |
| 6.4 BIPROPELLANT THRUSTORS | 129 |
| 7.0 SYSTEMS CONSIDERATIONS | 161 |
| 7.1 INTERFACES | 161 |
| 7.2 SYSTEM POWER | 164 |
| 7.3 THRUST VECTOR CONTROL | 166 |
| 7.4 THERMAL CONTROL | 168 |
| 7.5 LIFETIME | 171 |
| REFERENCES | 177 |
| LIMITATIONS SHEET | 179 |
| ACTIVE RECORD SHEET | 180 |
| REVISION SHEET | 182 |

USE FOR TYPEWRITTEN MATERIAL ONLY

LIST OF FIGURES

| | <u>PAGE</u> |
|--|-------------|
| 3.0-1 SPACE PROPULSION SYSTEMS | 13 |
| 3.0-2 SPACE PROPULSION SYSTEMS | 14 |
| 3.0-3 ROCKET ENGINES | 15 |
| 3.0-4 ROCKET ENGINES | 16 |
| 4.2-1 THRUSTOR PERFORMANCE IN PULSED OPERATION | 20 |
| 4.3-1 ROCKET ENGINE APPLICATION REGIONS - STEADY STATE OPERATION | 22 |
| 4.3-2 ROCKET ENGINE APPLICATION REGIONS - PULSED OPERATION | 25 |
| 4.3-3 TRANSIENT CONDITIONS | 27 |
| 4.3-4 THRUST RESPONSE | 29 |
| 4.3-5 ENGINE PERFORMANCE STEADY STATE | 29 |
| 5.1-1 THRUST COEFFICIENT AS A FUNCTION OF GAMMA (γ) | 37 |
| 5.1-2 MASS FLOW PARAMETER | 39 |
| 5.2-1 NOZZLE FLOW WITH A BOUNDARY LAYER | 40 |
| 5.2-2 VELOCITY COEFFICIENT | 42 |
| 5.2-3 DISCHARGE COEFFICIENT | 42 |
| 5.2-4 DIVERGENCE ANGLE EFFECTS ON THRUST COEFFICIENT | 44 |
| 6.1-1 TYPICAL COLD GAS SYSTEM | 48 |
| 6.1-2 TYPICAL COLD GAS THRUSTOR | 48 |
| 6.1-3 COLD GAS THRUSTOR - CONSTRUCTION DETAILS | 51 |
| 6.1-4 THEORETICAL PERFORMANCE OF COLD GAS FLUIDS | 54 |
| 6.2-1 TYPICAL HEATED GAS THRUSTOR | 61 |
| 6.2-2 LOW HEAT CAPACITY, FAST HEAT-UP HEATED GAS THRUSTOR | 64 |
| 6.2-3 WATER COOLED TUBULAR HEAT EXCHANGER THRUSTOR | 65 |
| 6.2-4 HIGH HEAT CAPACITY HEATED GAS THRUSTOR | 66 |
| 6.2-5 MOLECULAR WEIGHT OF THE EQUILIBRIUM $2\text{NH}_3 \rightleftharpoons \text{N}_2 + 3\text{H}_2$ SYSTEM | 69 |
| 6.2-6 DISSOCIATION EFFECTS ON PERFORMANCE OF HEATED AMMONIA THRUSTORS | 69 |
| 6.2-7 RESISTOJET POWER REQUIREMENTS, FAST HEAT-UP THRUSTOR | 72 |
| 6.2-8 RESISTOJET POWER REQUIREMENTS, THERMAL STORAGE THRUSTORS | 72 |
| 6.3-1 TYPICAL MONOPROPELLANT PROPULSION SYSTEM | 81 |
| 6.3-2 TYPICAL MONOPROPELLANT THRUSTOR | 81 |
| 6.3-3 HYDROGEN PEROXIDE DECOMPOSITION TEMPERATURE | 83 |

LIST OF FIGURES (continued)

| | <u>PAGE</u> |
|---|-------------|
| 6.3-4 HYDRAZINE PLENUM SYSTEM | 83 |
| 6.3-5 HYDRAZINE DECOMPOSITION GAS TEMPERATURE AND MOLE WEIGHT | 85 |
| 6.3-6 TYPICAL HYDROGEN PEROXIDE THRUSTOR | 87 |
| 6.3-7 TYPICAL HYDRAZINE THRUSTOR | 89 |
| 6.3-8 PHYSICAL PROPERTIES OF HYDROGEN PEROXIDE | 94 |
| 6.3-9 DENSITY OF HYDROGEN PEROXIDE | 95 |
| 6.3-10 PHYSICAL PROPERTIES OF HYDRAZINE | 98 |
| 6.3-11 FREEZING POINT OF HYDRAZINE AND WATER SOLUTIONS | 99 |
| 6.3-12 SPECIFIC GRAVITY OF HYDRAZINE AND WATER SOLUTIONS | 99 |
| 6.3-13 PHYSICAL PROPERTIES OF HYDRAZINE AND AMMONIA SOLUTIONS | 100 |
| 6.3-14 THEORETICAL PERFORMANCE OF COMMON MONOPROPELLANTS | 102 |
| 6.3-15 THEORETICAL PERFORMANCE OF HYDROGEN PEROXIDE | 102 |
| 6.3-16 SPECIFIC HEAT RATIO OF HYDROGEN PEROXIDE | 103 |
| 6.3-17 HYDROGEN PEROXIDE DELIVERED PERFORMANCE | 103 |
| 6.3-18 90 PERCENT HYDROGEN PEROXIDE PERFORMANCE IN PULSED OPERATION | 104 |
| 6.3-19 HYDROGEN PEROXIDE PERFORMANCE-DEMONSTRATED PULSE OPERATION | 104 |
| 6.3-20 HYDRAZINE PERFORMANCE CURVES | 106 |
| 6.3-21 STEADY STATE PERFORMANCE DELIVERED BY HYDRAZINE MONOPROPELLANT ENGINES | 107 |
| 6.3-22 HYDRAZINE MONOPROPELLANT ENGINES PULSE PERFORMANCE CAPABILITY | 107 |
| 6.3-23 MINIMUM IMPULSE BIT CAPABILITY OF HYDRAZINE ENGINES | 108 |
| 6.3-24 IMPULSE TOLERANCE HYDRAZINE ENGINES | 110 |
| 6.3-25 HYDRAZINE-HYDRAZINE NITRATE-WATER TERNARY DIAGRAM | 110 |
| 6.3-26 HYDROGEN PEROXIDE ENGINE CATALYST BED PRESSURE DROP | 113 |
| 6.3-27 CATALYST BED POROSITY-HYDRAZINE ENGINES | 116 |
| 6.3-28 CATALYST BED SURFACE AREA-HYDRAZINE ENGINES | 116 |

USE FOR TYPEWRITTEN MATERIAL ONLY

LIST OF FIGURES (continued)

| | <u>PAGE</u> |
|--|-------------|
| 6.4-1 ABLATIVE BIPROPELLANT ENGINE | 134 |
| 6.4-2 RADIATION COOLED BIPROPELLANT ENGINE | 136 |
| 6.4-3 REGENERATIVELY COOLED BIPROPELLANT ENGINE | 137 |
| 6.4-4 PHYSICAL PROPERTIES - NITROGEN TETROXIDE | 141 |
| 6.4-5 PHYSICAL PROPERTIES - MON 10 | 142 |
| 6.4-6 PHYSICAL PROPERTIES - INHIBITED RED FUMING NITRIC ACID (IRFNA) | 143 |
| 6.4-7 PHYSICAL PROPERTIES - CHLORINE TRIFLUORIDE | 145 |
| 6.4-8 PHYSICAL PROPERTIES - UNSYMMETRICAL DIMETHYL-HYDRAZINE (UDMH) | 146 |
| 6.4-9 PHYSICAL PROPERTIES - AEROZINE 50 | 147 |
| 6.4-10 PHYSICAL PROPERTIES - MONOMETHYL HYDRAZINE (MMH) | 149 |
| 6.4-11 THEORETICAL PERFORMANCE OF BIPROPELLANT COMBINATIONS | 150 |
| 6.4-12 BULK DENSITY OF BIPROPELLANT COMBINATIONS | 151 |
| 6.4-13 DELIVERED PERFORMANCE OF BIPROPELLANT ENGINES | 152 |
| 6.4-14 PERFORMANCE OF RADIATION COOLED PULSE ROCKET ENGINES | 152 |
| 6.4-15 TRANSIENT PERFORMANCE DATA, APOLLO ENGINE QUAL (LM-RCS) | 154 |
| 7.2-1 POWER REQUIREMENTS - EXISTING ENGINE VALVES | 165 |
| 7.2-2 POWER RESPONSE CHARACTERISTICS OF SOLENOID VALVES | 165 |
| 7.3-1 THRUST VECTOR CONTROL SYSTEM WEIGHT | 167 |
| 7.3-2 TYPICAL JET VANE TVC PERFORMANCE | 169 |
| 7.3-3 TYPICAL JET VANE ACTUATOR POWER REQUIREMENTS | 169 |
| 7.4-1 ENGINE EXTERNAL TEMPERATURE PROFILES | 170 |
| 7.4-2 HYDRAZINE ENGINE EXHAUST PLUME | 170 |
| 7.5-1 LIFETIME OF TUNGSTEN WIRES AND TUBES IN HYDROGEN | 172 |
| 7.5-2 TEMPERATURE AND PRESSURE EFFECTS ON LIFETIME OF TUNGSTEN WIRES AND TUBES | 172 |
| 7.5-3 CATALYST BED LIFE-HYDROGEN PEROXIDE | 174 |
| 7.5-4 CATALYST BED LIFE CHARACTERISTIC-HYDRAZINE ENGINES | 175 |

USE FOR TYPE-APPROPRIATE MATERIAL ONLY

LIST OF TABLES

| | <u>PAGE</u> |
|--|-------------|
| 6.1-1 CHARACTERISTICS OF SINGLE COMPONENT COLD GAS PROPELLANTS | 53 |
| 6.1-2 DEVELOPED COLD GAS THRUSTORS | 60 |
| 6.2-1 COMPARISON OF HEATED GAS THRUSTOR CONCEPTS | 63 |
| 6.2-2 RESISTOJET APPLICATIONS | 63 |
| 6.2-3 DEVELOPED HEATED GAS THRUSTORS | 77 |
| 6.3-1 PROPERTIES OF HYDROGEN PEROXIDE | 93 |
| 6.3-2 PROPERTIES OF HYDRAZINE | 97 |
| 6.3-3 DEVELOPED HYDROGEN PEROXIDE THRUSTORS | 125 |
| 6.3-4 DEVELOPED HYDRAZINE THRUSTORS | 128 |
| 6.4-1 BIPROPELLANT THRUST CHAMBER COMPARISON | 132 |
| 6.4-2 PHYSICAL PROPERTIES OF BIPROPELLANTS | 139 |
| 6.4-3 AVAILABLE BIPROPELLANT THRUSTORS | 159 |
| 7.1-1 ELECTRICAL, MECHANICAL AND STRUCTURAL INTERFACES | 162 |

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1.0 NOMENCLATURE

| | |
|---------------|--|
| A_c | catalyst bed frontal area |
| A_e | nozzle exit area |
| A_t | nozzle throat area |
| a^* | sonic velocity |
| C_D | discharge coefficient |
| C_F | nozzle thrust coefficient |
| C_v | velocity coefficient |
| c_p | specific heat at constant pressure |
| c_v | specific heat at constant volume |
| D_M | maximum diameter of thruster |
| D_{TC} | thrust chamber diameter |
| d_c | catalyst pack diameter |
| d_e | nozzle exit diameter |
| d_p | catalyst particle diameter |
| d_t | nozzle throat diameter |
| E_1 | dissociation potential (volts) of the propellant molecule |
| F | thrust |
| G | catalyst bed loading, propellant weight flow - catalyst bed frontal area |
| g_c | conversion constant |
| h_c | enthalpy of gas in combustion chamber |
| h_e | enthalpy of gas at nozzle exit |
| I_{sp} | specific impulse |
| I_t | total impulse |
| $I_{t_{min}}$ | minimum impulse bit |

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| | |
|-----------------|---|
| L^* | characteristic length of combustion chamber, chamber volume/ throat area |
| L_b | catalyst bed length |
| L_E | engine length |
| L_N | nozzle length |
| L_T | thruster length |
| L_{tc} | chamber length |
| \dot{m} | mass flow |
| N_T | number of injector orifices |
| P_a | ambient pressure |
| P_c | chamber pressure |
| P_e | nozzle exit pressure |
| P_i | input power |
| P_{in} | inlet pressure |
| P_j | jet power |
| P_{ss} | steady state pressure |
| ΔP_{CH} | catalyst bed pressure drop |
| ΔP_i | injector pressure drop |
| R | gas constant |
| Re | Reynolds number |
| S_o | spacing between orifice hole centers |
| T_c | gas temperature in the chamber |
| T_e | gas temperature at the exit |
| V_c | gas velocity in the chamber |
| V_C | chamber volume |
| V_e | gas velocity at the exit |
| W | mass flow parameter |

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| | |
|--------------|---------------------------------------|
| W_a | ablative engine weight |
| W_{cg} | cold gas thruster weight |
| W_E | engine assembly weight |
| W_R | radiation engine weight |
| \dot{w} | weight flow |
| α | nozzle divergence half angle |
| α | degree of dissociation |
| β | nozzle convergence half angle |
| γ | ratio of specific heats, c_p/c_v |
| δ^* | boundary layer displacement thickness |
| E | nozzle expansion ratio, A_e/A_t |
| ϵ_s | porosity of catalyst bed |
| η_c | engine efficiency |
| η_f | frozen flow efficiency |
| η_h | heater power efficiency |
| η_n | nozzle efficiency |
| λ | nozzle divergence correction factor |
| ρ_c | catalyst bed density |
| ρ_p | catalyst particle density |
| ρ_r | gas density at throat |
| ϕ | catalyst sphericity |

2.0 SUMMARY

Information on rocket engines using propellants stored as liquids or gases for use in attitude control and low velocity increment applications is presented. The thrust range for these engines is from micropounds to around 100 pounds.

Parameters which are important in the design or selection of a rocket engine for such applications are discussed and data from engines developed for spacecraft applications and research purposes presented. These include performance (both steady state and transient), weight, size envelope, reliability, life, power requirements, duty cycle, response, repeatability, cost and interface considerations.

The various types of rocket engines are discussed. These include cold gas, heated gas, monopropellant and bipropellant engines. The various propellants for each type of thruster are also discussed. Rocket engine performance is presented from both the theoretical standpoint and from compilation of delivered performance data for existing systems. A tabulation of transient performance for existing engines operating in the pulse mode is included.

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3.0 INTRODUCTION

To determine the performance of the various types of thermal and chemical propulsion systems, specific design data for the elements of the system are required as well as information on overall system performance. Similar information is required on the other systems - electric and nuclear in order to determine the best system for any particular application. Previous Boeing studies related to propulsion systems are indicated on the Figures 3.0-1 and 3.0-2 by document title and number. Future system work will be incorporated into the document series shown on Figure 3.0-2.

This document concerns itself with state-of-the-art and design data of one element in the system - the rocket engine. Previous work relating to all types of engines is shown in Figure 3.0-3. Future engine and thruster work will be incorporated into the document system shown on Figure 3.0-4. Access to information on the remaining propulsion elements beyond the overall systems and engines may be obtained through the Space Propulsion Systems - Concepts document (D2-113549-1).

Thermal and chemical propulsion technology has been and will continue to be the subject of considerable investigation by government agencies, educational institutions, and aerospace contractors. The purpose of this series of documents is to provide a central source of information generated by outside agencies as well as to provide a repository for related Boeing research.

The purpose of volume one of this document is to present information on engines used for reaction control systems and low velocity increment propulsion systems. The properties of the gases and liquid propellants used in these engines and some system considerations are also included.

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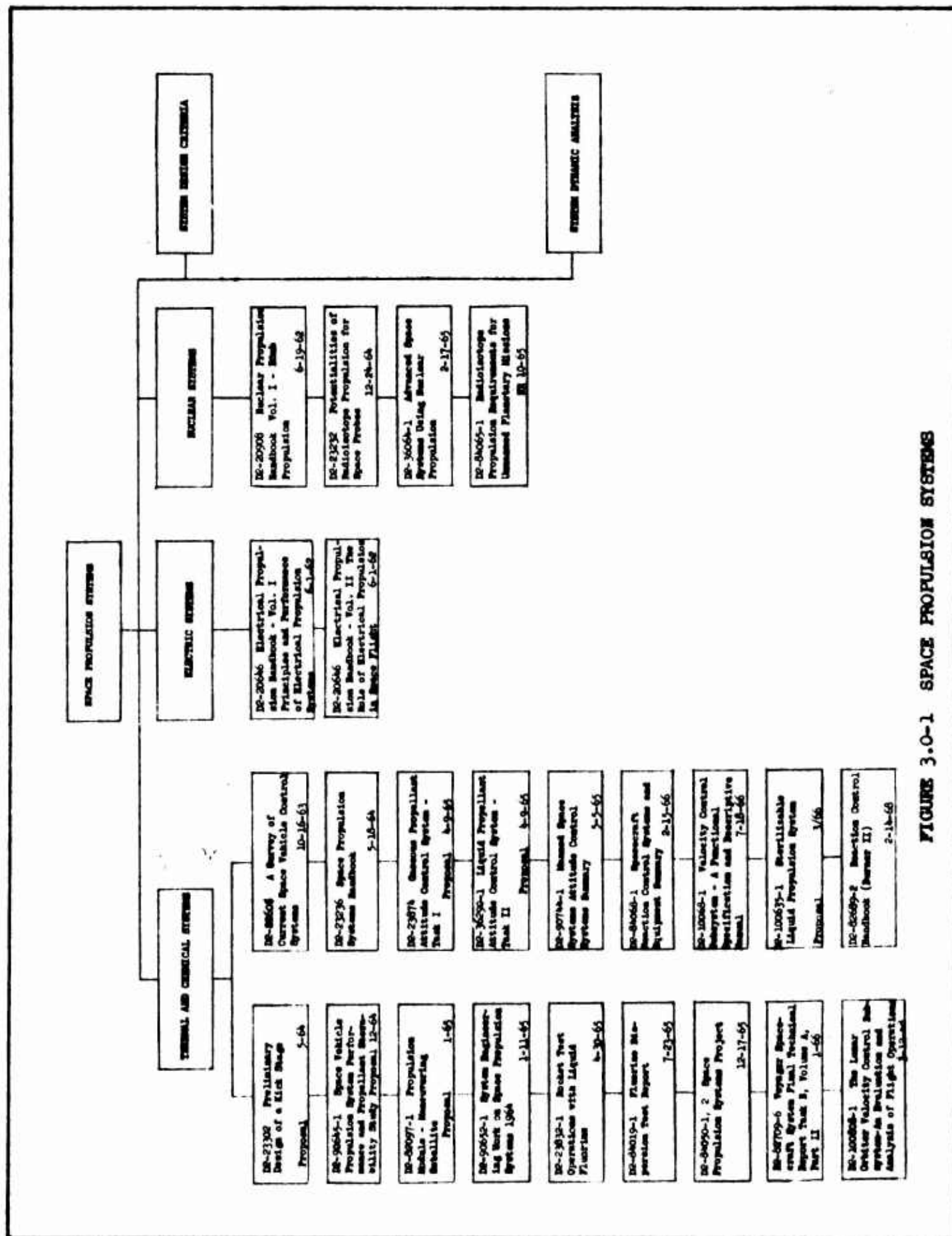


FIGURE 3.0-1 SPACE PROPULSION SYSTEMS

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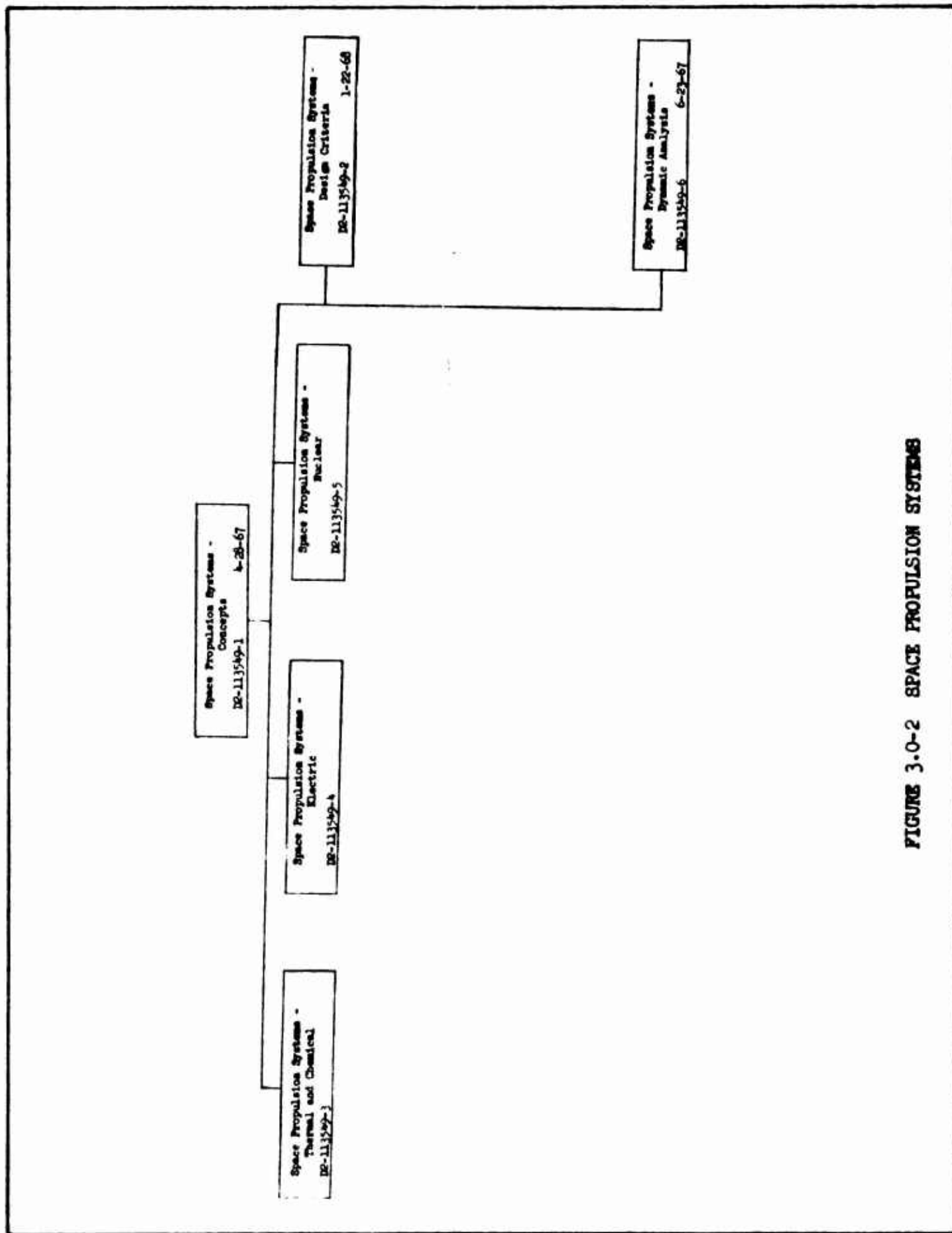
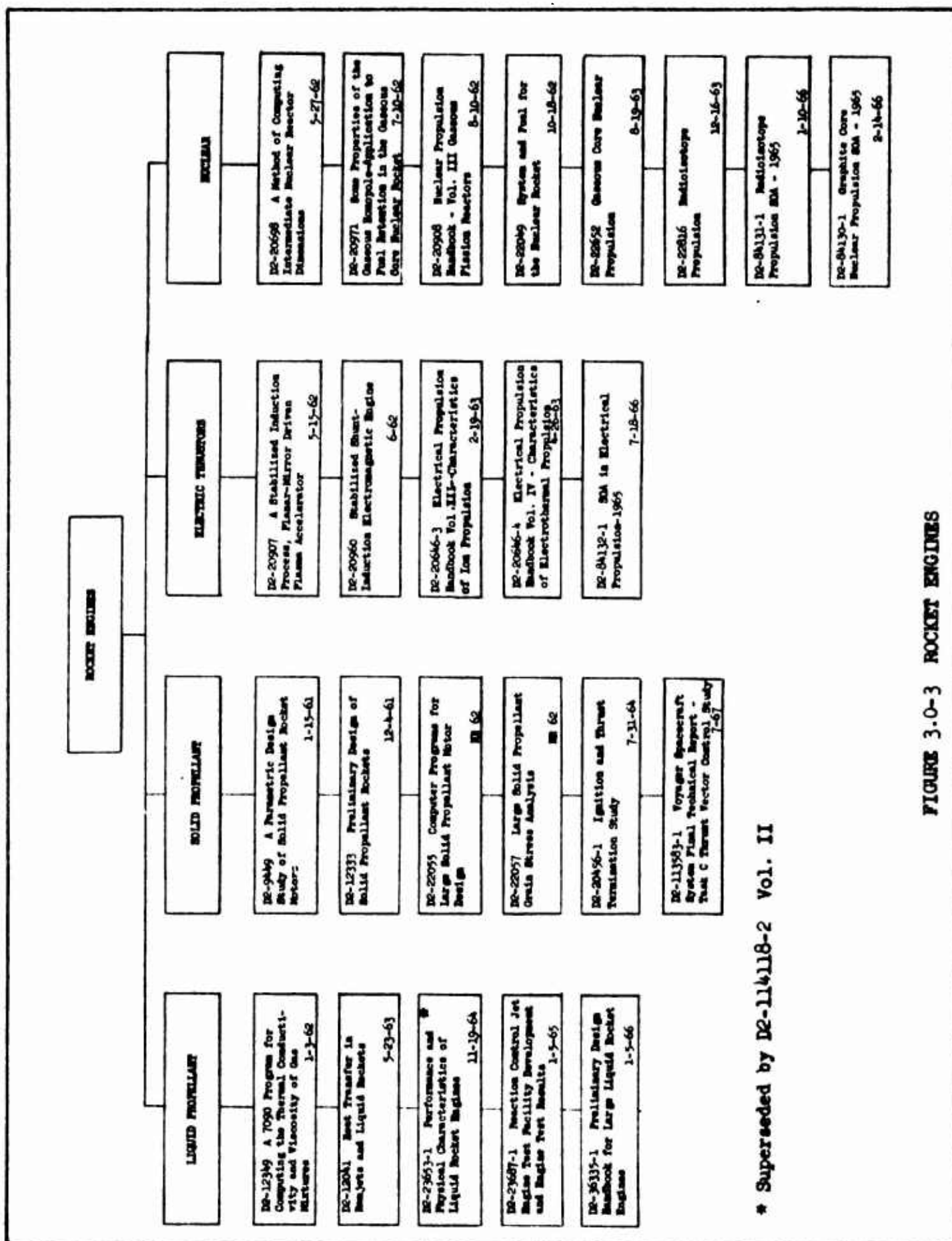


FIGURE 3.0-2 SPACE PROPULSION SYSTEMS

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FIGURE 3.0-3 ROCKET ENGINES

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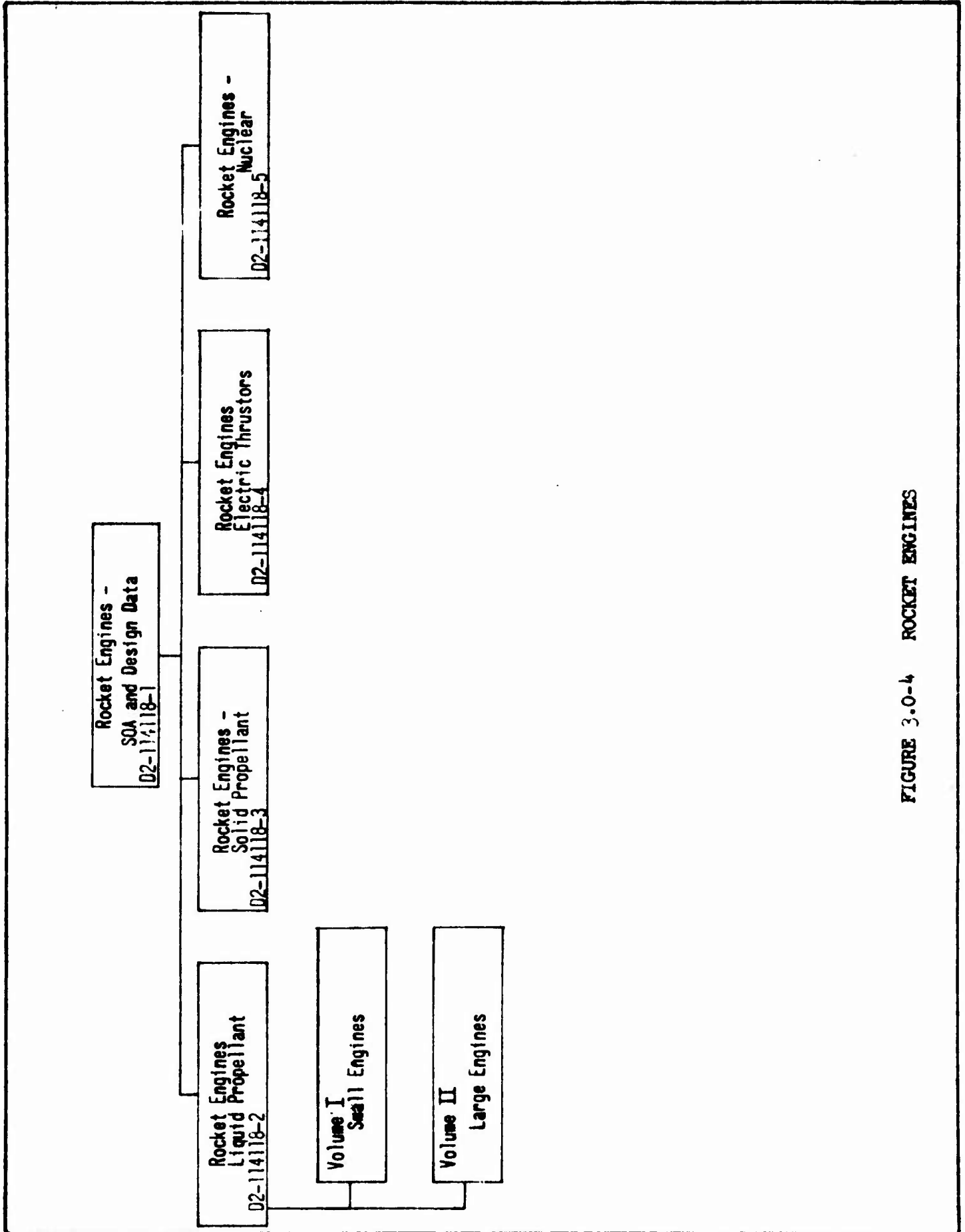


FIGURE 3.0-4 ROCKET ENGINES

4.0 MISSION REQUIREMENTS

Small rocket engines, or thrusters, are reaction devices used for translational and rotational control of spacecraft and boosters. Translational control is concerned with imparting a translational velocity in a specific direction. It is usually referred to as "velocity control" or "delta-v (ΔV) control". Rotational control, directed around a vehicle axis, is generally referred to as "reaction control" and is used in conjunction with other devices to provide vehicle attitude orientation and control. Velocity control and reaction control systems use similar components though their selection, design, installation and operating requirements may be considerably different.

4.1 VELOCITY CONTROL

Spacecraft velocity control systems are propulsion systems used for maneuvering, modifying trajectories, and for changing orbital characteristics. These applications entail certain unique features involving duty cycle, operating conditions, performance and the duration of space storage.

The number and duration of discrete operating sequences can usually be predicted from mission plans. For example, midcourse corrections are usually budgeted in a transfer trajectory to remove launch errors and to bias aiming point or arrival date. This budgeting involves relating the velocity corrections required, to propellant expenditures, while at the same time minimizing the number of maneuvers, commands and spacecraft functions required. Since velocity control systems usually operate for more than one second, thruster operation is considered to be steady state. Steady state performance is desirable since it minimizes transient effects, permits design for peak performance, and allows the thruster to reach operating temperature. Consequently, velocity control systems often make good use of the higher performance attained with monopropellant and

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bipropellant thrusters.

Propulsion system hardware is located, as much as possible, within the spacecraft.

The thrusters, however, must protrude in some fashion from the spacecraft.

Velocity control thrusters are usually closely coupled to the spacecraft along a major axis since the translational maneuvers they accomplish not require a moment arm. This eases the thermal control requirements concerned with preventing propellant freezing at the inlet lines. But it can complicate spacecraft thermal control requirements associated with engine, nozzle and exhaust plume heat loads.

Very small maneuvers are occasionally required from a velocity control system for midcourse correction, orbit trim, or similar uses. These small maneuvers require very small, precise and repeatable pulses (impulse bits) from the thrusters. These factors are controlled by thruster size, valve response and valve location.

The spacecraft must be properly oriented prior to a translational maneuver, and subsequently reoriented for the coast phase. This is a function of the attitude control system (ACS). During the maneuver, engine thrust vector control (TVC) is required to prevent it from introducing undesired moments about the spacecraft center of gravity.

Velocity control propulsion systems are selected on the basis of performance, weight, duty cycle and lifetime requirements, reliability and hardware availability. Velocity control thrusters and their valves are designed or selected on the basis of performance, response, repeatability, weight, size, lifetime, reliability, thermal characteristics, availability and various materials consideration. Primary criteria generally are specific impulse, minimum impulse bit, availability and weight.

4.2 REACTION CONTROL

Reaction control systems (RCS) are spacecraft propulsion systems used to provide spacecraft pitch, yaw and roll control. They are also used for attitude positioning when conducting major maneuvers, directing sensors, or aiming photographic systems. Their unique requirements concern system response, accuracy, duty cycle and component location.

Reaction control system thrusters usually operate in a pulsed mode to impart small impulse increments to the spacecraft about a specific axis. Consequently they are particularly characterized by transient and pulse mode factors including thrust rise and decay times and impulse bit size and shape. Overall performance is also quite important.

Reaction control thrusters are operated by attitude control system (ACS) commands. This system processes information about spacecraft orientation and relates it to desired orientation and maneuver rate to issue thruster "ON" and "OFF" signals. Hence, reaction control impulse bits are sized and scheduled against an assumed duty cycle based on anticipated disturbances, response rate limits, and scheduled spacecraft attitude positioning events. A "limit cycle" mode is usually used to accommodate induced disturbances by applying cycling response of the thrusters to a control band established by spacecraft pointing limits and control rate limits. These conditions are subsequently reduced to impulse bit size, duty cycle and propellant allowances. The pulse mode operation of reaction control thrusters with chemically reactive propellants yields lower performance than under steady-state conditions because of transient operation effects, engine thermal conditions, and single-versus-multiple design point considerations. The specific impulse of chemically

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reactive propellants approaches that of cold gas propellants with decreased pulse frequency and pulse width, as shown in Figure 4.2-1. Consequently, reaction control thrusters will not benefit from the higher performance propellants to the extent that velocity control thrusters do.

The reaction control system is usually installed in the spacecraft in a manner similar to that of velocity control systems. However, the thrusters are mounted at a distance from the spacecraft primary axes to provide moment arms for the rotational motions desired. Large moment arms permit small (lower thrust) engines which, in turn, are capable of smaller and more precise impulse bits. Propellant line length and electrical cabling increases correspondingly. These remote thruster locations also require some thermal protection whenever propellants are used which can freeze.

Reaction control propulsion systems are selected on the basis of response, repeatability, performance, reliability and availability. Primary criteria are specific impulse, minimum impulse bit, pulse width, thrust rise and decay time, and operating tolerances.

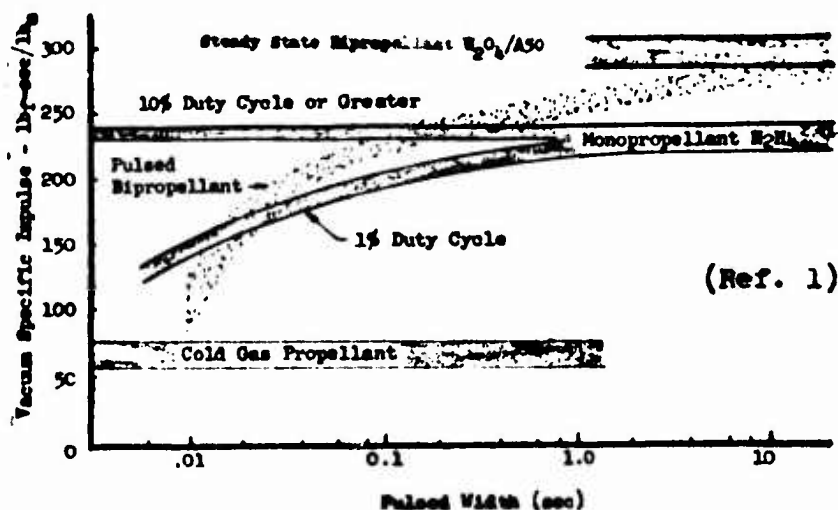


FIGURE 4.2-1 THRUSTER PERFORMANCE IN PULSED OPERATION

4.3 APPLICATIONS FOR LOW ΔV THRUSTORS

Small rocket engines or thrusters, have been extensively used for velocity and reaction control of satellites and boosters. This will increase with the increasing exploration and exploitation of space. Thruster selection is based on mission related factors (impulse, duty cycle measurements), system factors (thrust, weight, size), and engine characteristics (performance, response, induced environment). Hence, certain thruster types are appropriate to particular applications. These circumstances are discussed below.

4.3.1 Thrust and Impulse Effects

Engines used for translational maneuvering are commonly larger and operate less frequently than do engines used for attitude stabilization. Their operating duration per firing is longer, so steady state conditions are usually attained. Impulse requirements for translational maneuvering are large, so the higher performance of steady state operation helps to minimize propellant expenditures. Transient characteristics are less important with these engines, so they are generally designed for high performance rather than response.

Translational engines are often related to thrust and total impulse as shown in Figure 4.3-1. This figure shows that propulsion applications involving 100 to 100,000 lb-sec impulse and 0.01 to 100 lb thrust can be further defined by mission and thruster type. The boundaries to these regions are not hard and fast. They were derived from numerous system, mission, and engine studies some of which undoubtedly were resolved by other factors such as reliability. Nevertheless, this figure serves a useful function in simplifying a complex situation to the extent that application trends are apparent.

Impulse (i.e. propellant) requirements are a strong function of maneuver velocity. They increase with velocity capability to the extent that system weight becomes

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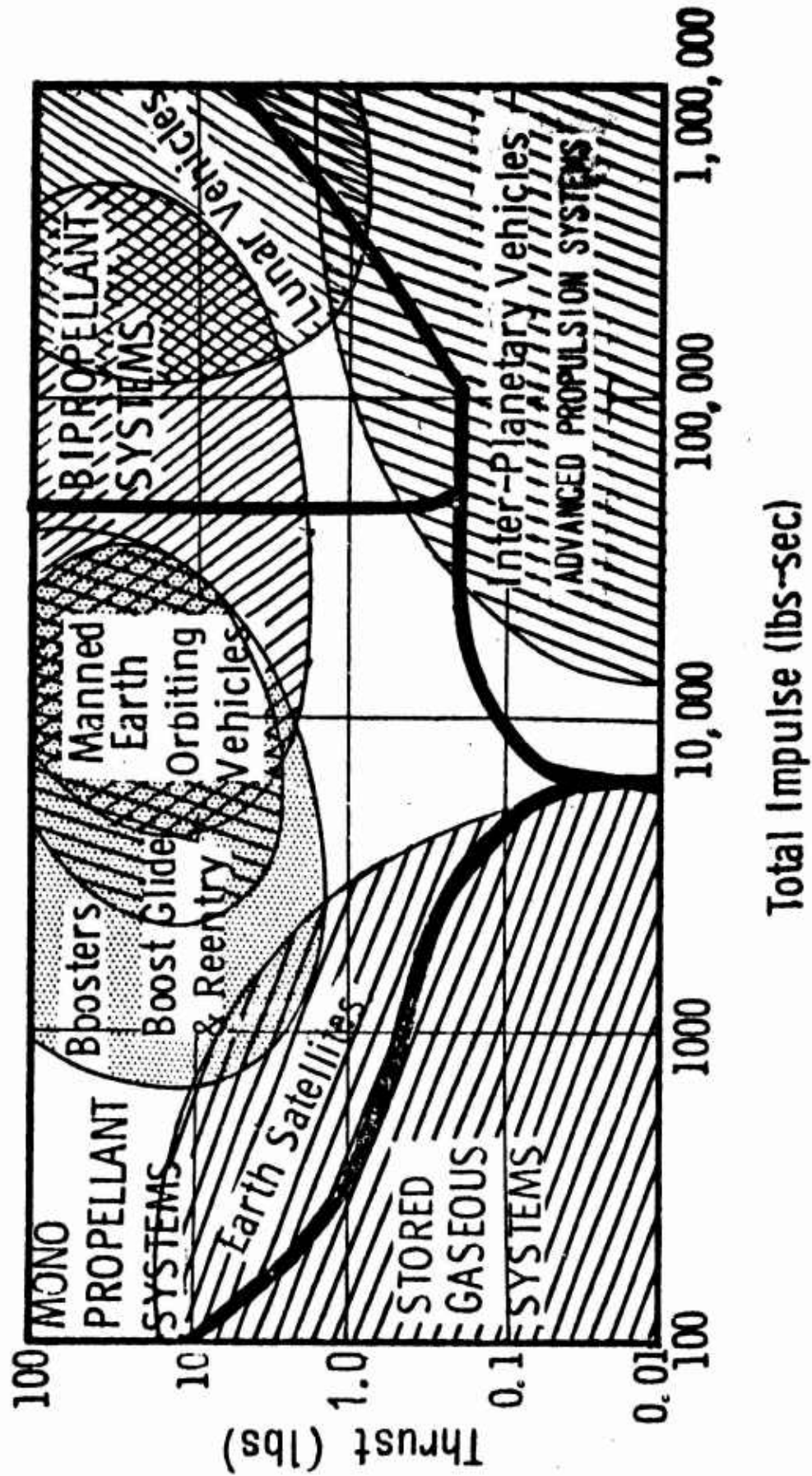


FIGURE 4.3-1 ROCKET ENGINE APPLICATION REGIONS - STEADY STATE

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increasingly a function of propellant loading. Under these circumstances, the higher performance propulsion systems may offer significant weight advantages. Propulsion systems are sometimes used for several maneuvers which may permit the use of higher energy systems. For example, Lunar Orbiter performed both midcourse correction (small ΔV) and orbit insertion (large ΔV) with the same bipropellant engine. Surveyor uses three bipropellant engines for midcourse correction, attitude control during solid motor firing, and vernier control for maneuvering and soft landing. Ranger and Mariner, however, used their monopropellant hydrazine systems only for midcourse correction maneuvers. The performance advantage of monopropellant engines in the Ranger program and bipropellant engines in Surveyor were enough to offset their development. Mariner hardware and technology was derived from Ranger. Lunar Orbiter used Apollo program bipropellant technology. Thus, velocity control systems used in the 150-4000 fps velocity and 550-2500 lb spacecraft weight range currently use the higher performance monopropellant or bipropellant engines since the technology, hardware, and space experience are available.

Impulse requirements are proportional to spacecraft size. It has been mentioned that propulsion system weight becomes increasingly a function of propellant weight with larger systems. Thus, propulsion systems for large spacecraft can derive a distinct weight advantage from using the higher performance monopropellant and bipropellant engines. The larger spacecraft currently occur in the manned Apollo and Manned Orbiting Laboratory (MOL) programs. Maneuvering and attitude control engines in the Mercury Spacecraft (Apollo Program) used monopropellant hydrogen peroxide thrusters. The succeeding Gemini spacecraft used bipropellant engines for maneuvering and attitude control as will the Apollo Command (CM), Service (SM) and Lunar (LM) modules.

Less impulse is usually required for attitude positioning and control than for performing major maneuvers. The impulse capability provided to satellites, especially earth satellites, is primarily for attitude control and is thus not large in magnitude. The pulsing duty cycle employed for reaction control reduces the performance advantage of monopropellant or bipropellant thrusters over stored gas thrusters (cold or heated gas). Also, the weight of small propulsion systems is strongly influenced by components which are not strongly weight-sensitive to thrust level or propellant loading such as standard components sizes, fittings, bosses, mounts, cabling and wiring. As a consequence, the lower performance cold gas systems have been competitive on a weight basis and have distinct advantages in simplicity and hardware availability. When velocity requirements increase, such as for velocity control purposes, a weight advantage accrues to monopropellant and bipropellant propulsion systems, since engine performance is highest when operating under steady-state conditions.

Monopropellant engines will increase in use as hardware experience, performance and availability increases. Hydrogen peroxide (H_2O_2) has been recently used as a monopropellant with good success on several satellites, including Syncom and Comsat. It had previously been used as a monopropellant for reaction control and auxiliary power on the X-1 and X-15 rocket aircraft, and the Centaur upper stage booster.

Boosters and maneuvering stages have frequently had pulsed bipropellant engines for reaction control using the primary propellants. Recently, monopropellant engines have been introduced into booster system use with the Burner II upper stage using hydrogen peroxide for reaction control. Significantly, the bipropellant attitude control and maneuvering engines on Titan II Transtage have been changed to monopropellant hydrazine engines using the Shell 405

spontaneous catalyst.

4.3.2 Response and Impulse Bit Effects

Thrusters used for very small velocity corrections, attitude positioning, and attitude control are particularly affected by engine pulsing characteristics, especially thrust response and impulse bit size. Good pulsing characteristics are measured in terms of good repeatability, small minimum impulse bits, rapid thrust rise and decay times, high performance, and long operating life. Figure 4.3-2 is a generalized guide for selecting engines to be used in pulsing applications in which minimum bit size is important. This figure shows discrete regions of thrust and minimum impulse in which particular types of engines (i.e., stored gas, monopropellant or bipropellant) are appropriate. The boundary describing the lowest minimum impulse bit in each area indicates the best pulsing capability of close-coupled, fast response thruster systems. Adjacent to these regions are arrows indicating the particular type of mission to which these engines are suited. This figure shows especially that unmanned earth orbital, lunar and interplanetary satellites are the spacecraft which require

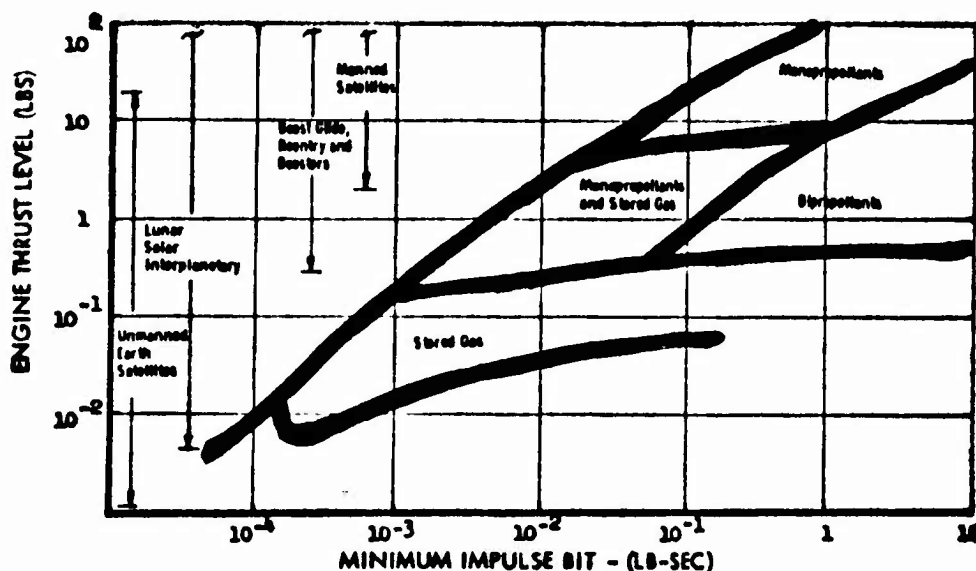


FIGURE 4.3.2 ROCKET ENGINE APPLICATION REGIONS-PULSED OPERATION

engines of less than 1 pound thrust and 10^{-2} lb-sec minimum impulse bit capability. Boosters, reentry and boost glide vehicles and manned satellites use larger engines which have larger minimum impulse bits. Future large unmanned satellites may use larger engines, but they may still need relatively small minimum impulse bits. Small engines will be used in applications involving the smaller satellites, low maneuver rates, extremely fine pointing requirements or where they are used in conjunction with other attitude stabilization devices.

Response characteristics are transient conditions involving chamber pressure, thrust, impulse and time during the start-up and shutdown phases. Transient effects are more pronounced with small pulses, slow acting valves, large thrust chambers, low propellant temperatures and, sometimes, with increased pulse spacing. Transient conditions including ignition delay, thrust build-up and thrust decay are shown in Figure 4.3-3. Some differences exist in the industry concerning the meaning of these terms, especially as they apply to different engine types. Ignition delay is used herein for that period of time consumed between initiation of the electrical ignition signal and first detection of a corresponding reaction in chamber pressure. This includes time increments involved in electrical and electro-mechanical delays, propellant transport lag and delays in chemical reaction initiated by hypergolic, electrical, thermal or catalytic means. Bipropellant engine manufacturers sometimes use the term "ignition delay" for what is actually the chemical reaction delay. Thrust build-up and decay periods are defined by the time required to reach a specific thrust level. They are usually given as a percent of maximum steady state thrust and measured in terms of equivalent chamber pressure.

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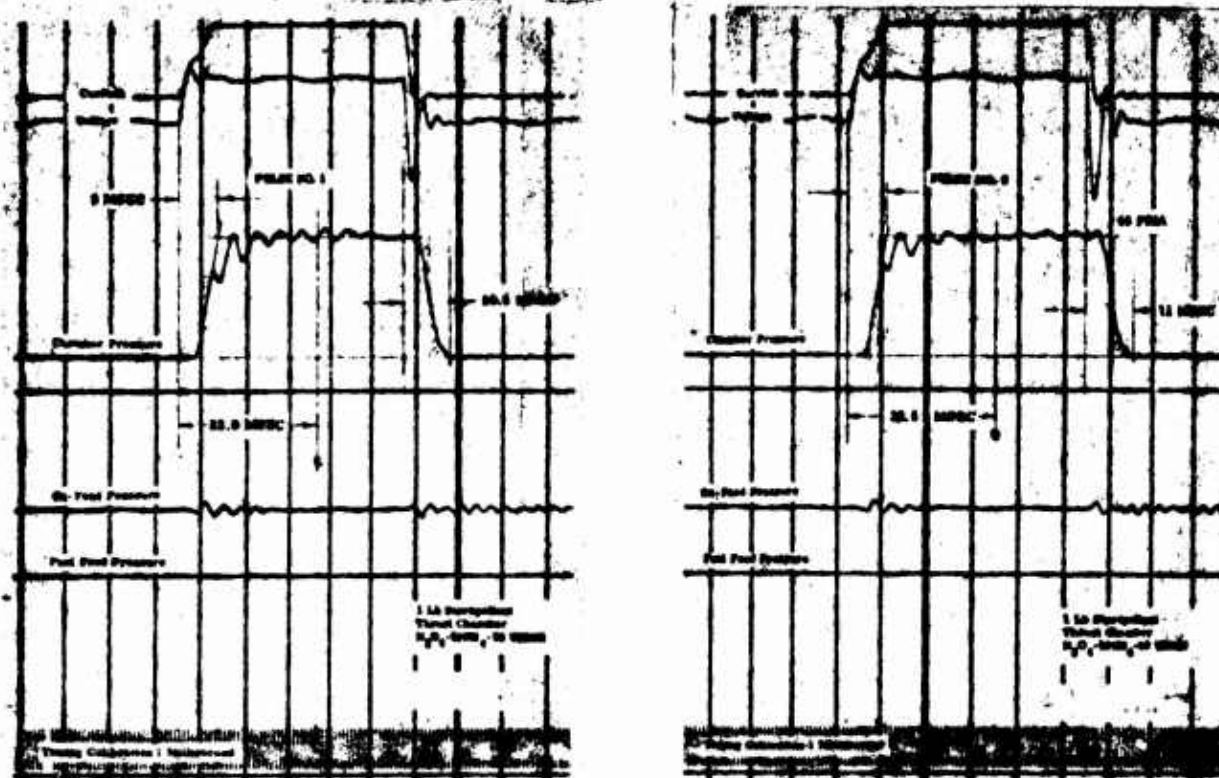


FIG. 4.3-3 TYPICAL ROCKET ENGINE TRANSIENT CONDITIONS (Ref. 3)

Figure 4.3-3 shows two pulses from a sequence of ten obtained with a small bi-propellant thruster operated at a nominal duty cycle of 9%. This sequence shows transient characteristics and reproducibility of chamber pressure, propellant inlet pressure, and valve current and voltage as the valve is actuated for each pulse. The chamber pressure trace shows that eleven (11) msec. were consumed between the application of valve voltage and reaching rated thrust. Approximately four (4) msec. of this were taken up by the electrical delay and valve poppet opening time. The remaining seven (7) msec. include the injector and feed tube filling time, propellant ignition delay, and the time required to fill the chamber volume with combustion gases. The shutdown transient consumed approximately eleven (11) msec. between removing valve power and attaining essentially 0% thrust. This time was consumed in electrical delay, valve poppet closing, emptying the "dribble volume", and emptying the chamber of gases.

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Engine response characteristics are primarily controlled by the chamber design and the valve-chamber relationship. These characteristics depend on the valve actuation time, and the propellant volume contained between the valve and the injector ("hold-up volume"). When quick response is desired for rapid thrust build-up or pulsing operation, fast acting valves are closely mated to the engine to minimize propellant "hold-up volume." Such engines are referred to as "fast-acting" and "close-coupled." Thrust chamber volume is important because small thruster chambers have faster response characteristics. For quick response, chamber volume should be as small as possible, though not so small that performance is reduced through incomplete combustion. Chamber size is described in terms of L^* , the chamber characteristic length, which is equal to the chamber volume per unit of nozzle throat area. Figure 4.3-4 shows how ignition delay increases with L^* . Figure 4.3-5 shows how (1) performance decreases with decreasing L^* and (2) that there is a performance difference in chemical engines designed for pulse-mode operation as opposed to those desired for single point, steady-state operation.

Characteristic length (L^*) affects response in cold gas systems, but it does not affect performance since chemical reactions are not involved. Chamber temperature of cold gas thrusters is constant except as it is influenced by variations in state or source temperatures. Consequently, cold gas thruster performance, though comparatively low, is constant and predictable throughout system operation, simplifying the design of attitude control logic.

Monopropellant engines do not behave in this fashion. Since they are designed to operate at elevated temperature, performance is variable until stable operating conditions exist. This happens when the engine and catalyst have been raised to operating temperature by heat obtained from the

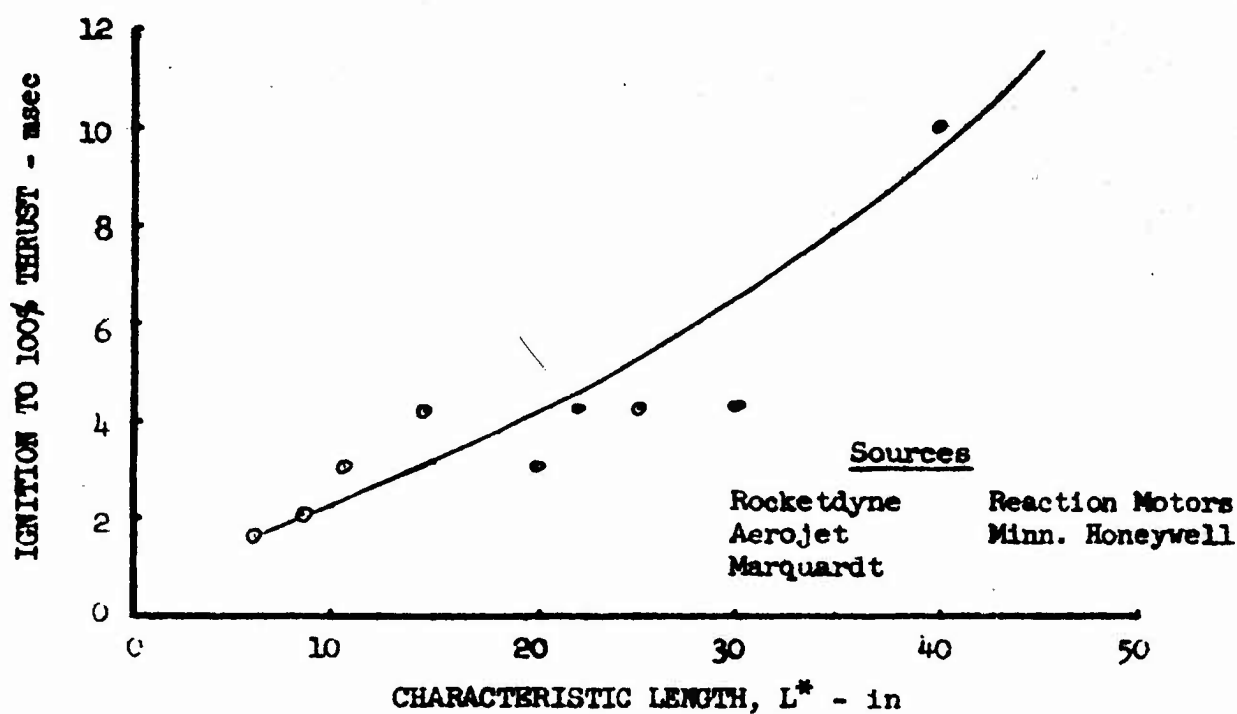


Figure 4.3-4

THRUST RESPONSE

(Ref. 4)

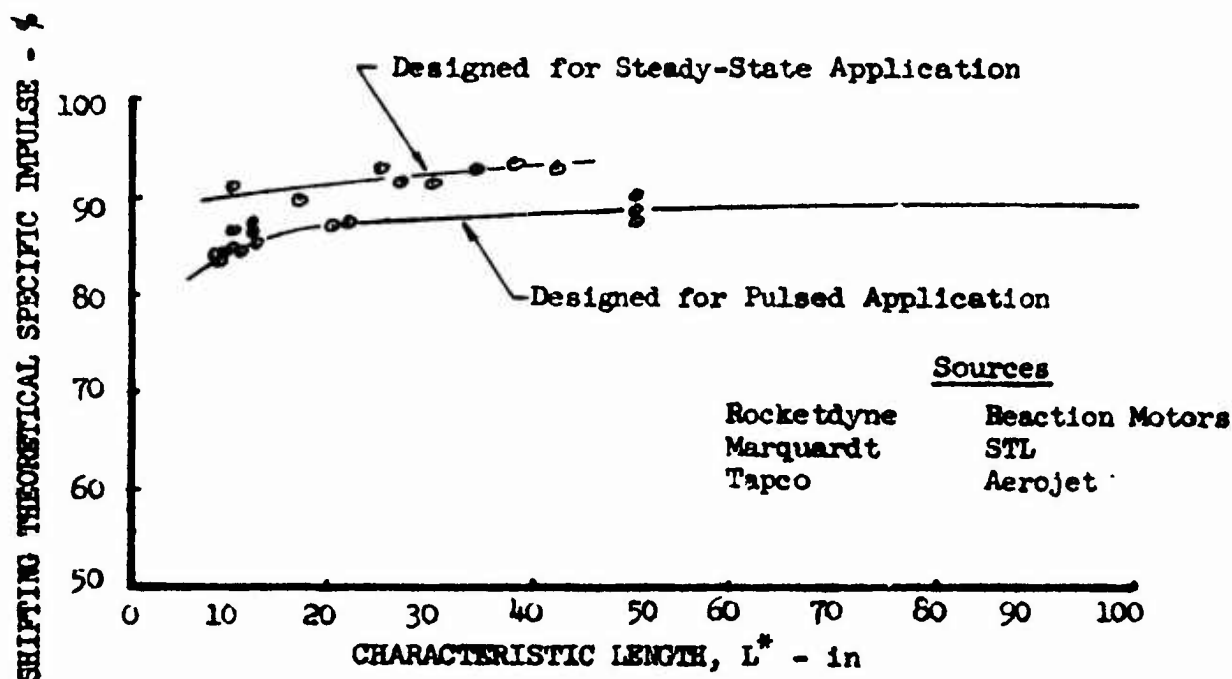


Figure 4.3-5 ENGINE PERFORMANCE STEADY-STATE

(Ref. 4)

decomposition process. Performance is reduced, and thrust rise times extended, until stable operating conditions are attained. Thus, monopropellant engines do not exhibit uniform performance and response characteristics under all operating conditions.

Translational maneuvers are controlled by either a timer or an accelerometer. Maneuver rate data is used to control attitude orientation maneuvers. Timed maneuvers accumulate deviations from scheduled performance as a total error at end burn. Maneuvers controlled by accelerometer or rate data correct for these deviations accumulating only those errors attributable to instrumentation tolerance and thrust tailoff variations. An additional error may develop from interference in pulse scheduling when response is so slow that additional pulses are commanded before previously ordered pulses are detected. This is particularly appropriate to "cold" (ambient) monopropellant engines. Maneuver error is greatest with timed maneuvers, being generally on the order of 10-30% for very small maneuvers (≈ 0.10 m/sec) and 3-7% for large maneuvers (≈ 1.0 m/sec). In most installations accelerometer control can be justified for maneuvers exceeding 0.1 to 10.0 m/sec.

Bipropellant engines lose little performance to engine warm-up since combustion temperatures are so much higher ($5000-6000^{\circ}\text{F}$) than with monopropellants ($1800-3300^{\circ}\text{F}$) that it is necessary to keep the chamber walls from overheating. These engines depend, to some extent, on film cooling by using a fuel rich barrier at the chamber walls. Since no catalyst is required there is little interior chamber mass to be brought up to operating temperature. Pulsed bipropellant engines do lose some performance due to mixture ratio variations, though impulse variations appear to be small and reasonably linear. When a bipropellant engine is required to operate in a pulse mode it is specifically designed for these

conditions. It usually has lower steady state performance, as shown in Figure 4.3-5, but for a particular design, performance and response is consistent over a wide range of operating conditions. It can thus be used in timed, accelerometer controlled, and rate controlled maneuvers with relatively simple control logic.

Fast acting propellant valves are necessary to quick engine response. These valves must be capable of rapid and positive response. Direct acting solenoid valves or torque motor actuated valves are usually preferred. Typical valve actuation periods are in the 5-10 millisecond range.

Cold-gas thrusters have superior response capability in that fast acting, close-coupled hardware can be used, thrust characteristics are relatively insensitive to propellant or hardware temperature, and simple control logic can be used. Response of cold gas engines is limited by valve capability which is currently on the order of 5-7 milliseconds. Transport lag can be as brief as 1-3 milliseconds. Time to 90% thrust then can be less than 7 milliseconds. Repeatability of cold gas engines is quite high.

Monopropellant systems have larger hold-up volumes due to valve and injector design requirements so that transport lag with the liquid monopropellant is somewhat higher. Monopropellant engines will, in pulsing operation, be somewhat less repeatable since the volume uncertainties involve liquids instead of gases, and response characteristics are influenced by thermal conditions. Response to 90% thrust exceeds 7 milliseconds for small monopropellant thrusters designed for pulsing operation and operated with ambient propellants and a hot catalyst bed. Performance is higher than with most cold gas engines.

Bipropellant systems have hold-up volume and hydraulic lag effects in both the fuel and oxidizer circuits and, in addition, they require some degree of mixture ratio control. In small engines, transport lag may consume 4-5 milliseconds. Smaller, fast-response, close-coupled bipropellant engines are capable of 15-25 milliseconds response to 90% thrust.

4.3.3 Packaging Effects

Propulsion system installed volume may, at times be an important factor due to limitations imposed by the booster, shroud, spacecraft structure, or experiments. Cold gas systems are inferior in this regard since a relatively large amount of propellant is stored in the gaseous state. However, cold gas equipment may be easier to position on the spacecraft since there is no danger of propellant freezing. Additionally, cold gas thrusters have minimum thermal interference with adjacent spacecraft equipment.

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5.0 ROCKET ENGINE PERFORMANCE

The basic steady-state performance equations for rocket engines are developed in detail in numerous textbooks among which are References 5 and 6. These equations are briefly developed herein to support subsequent discussions of delivered steady-state performance, and of transient performance.

5.1 THEORETICAL STEADY STATE PERFORMANCE

The theoretically ideal rocket is based on adiabatic, steady state flow of **homogeneous**, compositionally invariant propellants (in chemical equilibrium) which obey the perfect gas laws, which develop no friction, and which have uniform, axially directed velocity. These assumptions permit one-dimensional analyses of the rocket engine.

Rocket engine thrust is defined by a momentum plus pressure-time-area term:

$$F = \dot{m} V_e + [P_e - P_a] A_e \quad (5.1-1)$$

The principle of conservation of energy is used for gas velocity at the nozzle exit. For an adiabatic gas expansion (no heat transfer between the gas and nozzle) having no friction between the gas and the nozzle wall, the conservation of energy requires the decrease in gas enthalpy to be equal to the increase in gas kinetic energy. That is,

$$h_c - h_e = \Delta h = [V_e^2 - V_c^2] / 2g_c \quad (5.1-2)$$

For a perfect gas

$$h_c - h_e = \Delta h = C_p [T_c - T_e] \quad (5.1-3)$$

$$C_p = \frac{\gamma R}{\gamma - 1} \quad (5.1-4)$$

For an isentropic process,

$$\frac{T_c}{T_e} = \left[\frac{P_c}{P_e} \right]^{\frac{\gamma-1}{\gamma}} \quad (5.1-5)$$

Assuming that the chamber cross-sectional area is large compared to the throat area, v_c is small and can be neglected:

$$V_e = \left\{ \left[\frac{2\gamma}{\gamma-1} \right] R T_c \left[1 - \left(\frac{P_e}{P_c} \right)^{\frac{\gamma-1}{\gamma}} \right] \right\}^{1/2} \quad (5.1-6)$$

The mass flow rate equals:

$$\dot{m} = \frac{\dot{w}}{g_c} = \frac{P_c}{g_c} A_t V_t \quad (5.1-7)$$

The throat velocity v_t is equal to the speed of sound at the throat, which is

$$V_t = \left[\left(\frac{\gamma}{\gamma+1} \right) R T_c \right]^{1/2} \quad (5.1-8)$$

The flow density at the throat is related to the chamber density by

$$\frac{\rho_t}{\rho_c} = \left[\frac{2}{\gamma+1} \right]^{1/(\gamma-1)} \quad (5.1-9)$$

Using the ideal gas relationship,

$$\rho_c = \frac{P_c}{R T_c} \quad (5.1-10)$$

and substituting equations (5.1-8) and (5.1-9) into equation (5.1-7) gives

$$\dot{m} = \left[\frac{P_c A_t \gamma}{(\gamma g_c R T_c)^{1/2} \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{2(\gamma-1)}}} \right] \quad (5.1-11)$$

Combining equations (5.1-6) and (5.1-11) into (5.1-1)

$$F = P_c A_t \gamma \left[\frac{2}{\gamma+1} \right]^{\frac{\gamma+1}{2(\gamma-1)}} \left\{ \frac{2}{\gamma-1} \left[1 - \left(\frac{P_e}{P_c} \right)^{\frac{\gamma-1}{\gamma}} \right] \right\}^{\frac{1}{2}} + P_e A_e \quad (5.1-12)$$

Equation 5.1-12 is generalized, non-dimensionally, to:

$$C_F = \frac{F}{P_c A_t} = \gamma \left[\frac{2}{\gamma+1} \right]^{\frac{\gamma+1}{2(\gamma-1)}} \left\{ \frac{2}{\gamma-1} \left[1 - \left(\frac{P_e}{P_c} \right)^{\frac{\gamma-1}{\gamma}} \right] \right\}^{\frac{1}{2}} + \frac{P_e A_e}{A_t P_c} \quad (5.1-13)$$

The term A_e/A_t is evaluated by applying the principle of conservation of matter:

$$\rho_t A_t V_t = \rho_e A_e V_e \quad (5.1-14)$$

Noting that,

$$\frac{\rho_t}{\rho_e} = \frac{\rho_t}{\gamma} \cdot \frac{\gamma}{\rho_e} \quad (5.1-15)$$

and applying the isentropic flow relations,

$$\frac{\rho_t}{\rho_e} = \left(\frac{P_t}{P_e} \right)^{\frac{1}{\gamma}} \quad \text{and} \quad \frac{\gamma}{\rho_e} = \left(\frac{\gamma+1}{2} \right)^{\frac{1}{\gamma-1}} \quad (5.1-16)$$

the term ρ_t/ρ_e becomes

$$\frac{\rho_t}{\rho_e} = \left(\frac{P_t}{P_e} \right)^{\frac{1}{\gamma}} \left(\frac{\gamma}{\rho_e} \right)^{\frac{1}{\gamma}} = \left(\frac{\gamma}{\gamma+1} \right)^{\frac{1}{\gamma-1}} \left(\frac{P_e}{P_c} \right)^{\frac{1}{\gamma}} \quad (5.1-17)$$

Combining equations (5.1-17), (5.1-3), (5.1-6) and (5.1-14), the area ratio equals

$$\frac{A_e}{A_t} = \left(\frac{\gamma}{\gamma+1} \right)^{\frac{1}{\gamma-1}} \left(\frac{P_e}{P_c} \right)^{\frac{1}{\gamma}} \left\{ \left(\frac{\gamma-1}{\gamma+1} \right) \left[1 - \left(\frac{P_e}{P_c} \right)^{\frac{\gamma-1}{\gamma}} \right] \right\}^{\frac{1}{2}} \quad (5.1-18)$$

Thus

$$C_{F_i} = \gamma \left\{ \left(\frac{\gamma}{\gamma-1} \right) \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}} \left[1 - \left(\frac{P_e}{P_c} \right)^{\frac{\gamma-1}{\gamma}} \right] \right\}^{\frac{1}{2}} + \left(\frac{P_e}{P_c} \right)^{\frac{\gamma-1}{\gamma}} \left(\frac{2}{\gamma+1} \right)^{\frac{1}{\gamma-1}} \left\{ \left(\frac{\gamma-1}{\gamma+1} \right) \left[1 - \left(\frac{P_e}{P_c} \right)^{\frac{\gamma-1}{\gamma}} \right] \right\}^{\frac{1}{2}} \quad (5.1-19)$$

A plot of this equation is shown in Figure 5.1-1. It contains a velocity thrust coefficient (C_{F_V}) and a pressure thrust coefficient (C_{F_P}), such that:

$$C_{F_i} = C_{F_V} + C_{F_P} \quad (5.1-20)$$

where:

$$C_{F_P} = \left(\frac{P_e}{P_c} \right)^{\frac{\gamma-1}{\gamma}} \left(\frac{2}{\gamma+1} \right)^{\frac{1}{\gamma-1}} \left\{ \left(\frac{\gamma-1}{\gamma+1} \right) \left[1 - \left(\frac{P_e}{P_c} \right)^{\frac{\gamma-1}{\gamma}} \right] \right\}^{\frac{1}{2}} \quad (5.1-21)$$

$$C_{F_V} = \gamma \left\{ \left(\frac{\gamma}{\gamma-1} \right) \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}} \left[1 - \left(\frac{P_e}{P_c} \right)^{\frac{\gamma-1}{\gamma}} \right] \right\}^{\frac{1}{2}} \quad (5.1-22)$$

Specific impulse, I_{sp} , equals:

$$I_{sp_i} = \frac{F}{\dot{m}} \quad (5.1-23)$$

Combined with (5.1-11), (5.1-13), this becomes:

$$I_{sp_i} = \frac{F}{\dot{m}} = \frac{C_{F_i}}{\gamma} \left[\frac{\gamma R T_c}{g \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}}} \right]^{\frac{1}{2}} \quad (5.1-24)$$

Equation (5.1-24) can be further simplified to

$$I_{sp_i} = \frac{C_{F_i}}{W} \left[\frac{T_c}{m} \right]^{\frac{1}{2}} \quad (5.1-25)$$

by defining a weight flow parameter, W , as

$$W = \left[\frac{\gamma g \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}}}{K_c} \right]^{\frac{1}{2}} \quad (5.1-26)$$

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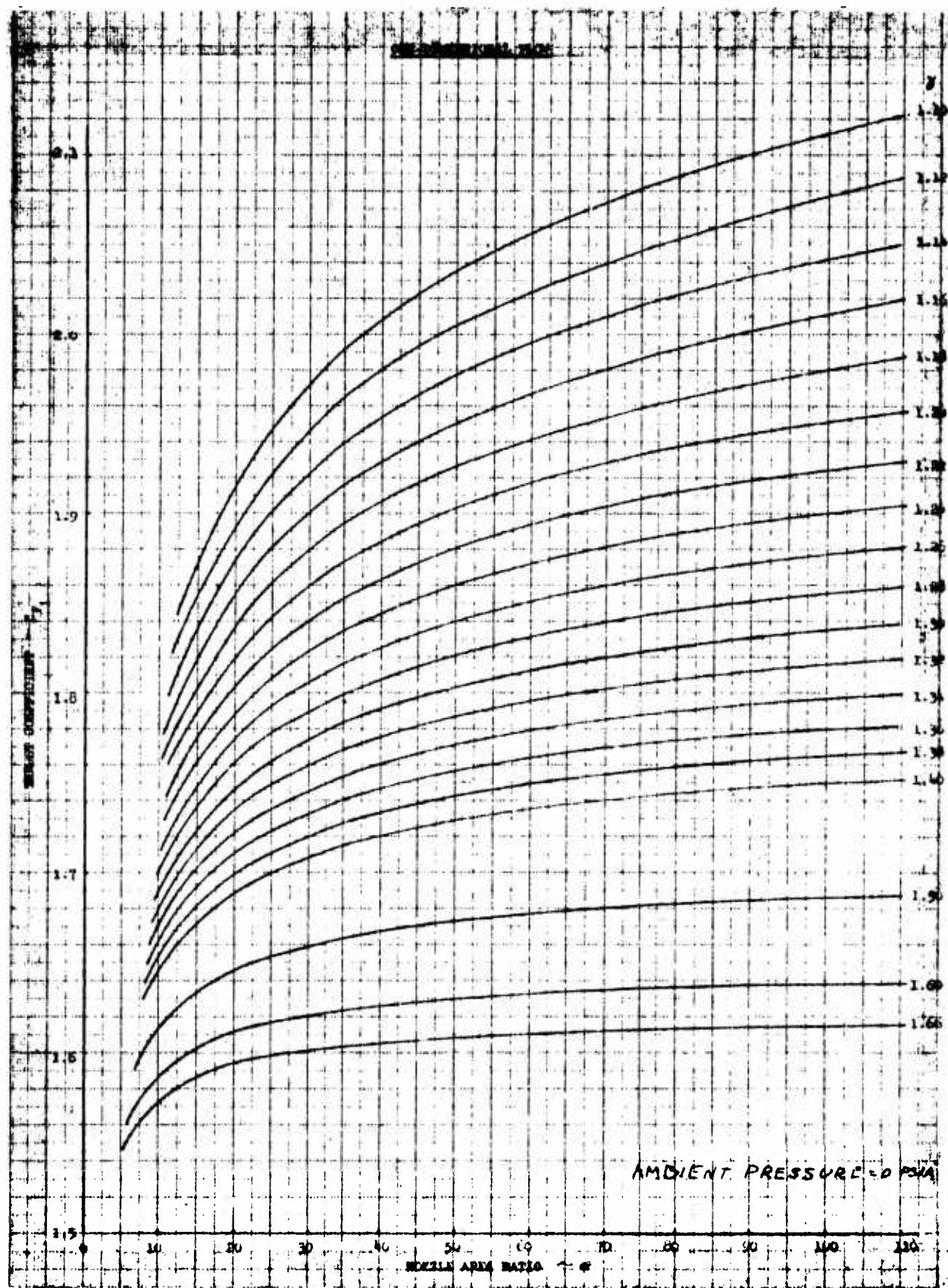


Figure 5.1-1 THRUST COEFFICIENT AS A FUNCTION OF GAMMA

so that

$$\dot{m} = W P_c A_t \left[\frac{\gamma}{T_c} \right]^{1/2} \quad (5.1-27)$$

Equation 5.1-19 is shown graphically in Figure 5.1-1 for specific heat ratios of 1.1 to 1.66. Equation 5.1-26 is shown graphically in Figure 5.1-2 for specific heat ratios from 1.1 to 1.7. These equations assume a constant specific heat ratio during the expansion process. In general, this is a valid assumption because the effects of temperature and pressure on specific heat ratio are small.

5.2 DELIVERED STEADY-STATE PERFORMANCE

Delivered performance differs from theoretical values because actual conditions vary from those assumed in the ideal case. Primary variations can be attributed to boundary layer effects, nozzle divergence angle effects, and non-homogenous, chemically changing propellant conditions during the flow process.

5.2.1 BOUNDARY LAYER EFFECTS

The effect of boundary layer growth on nozzle performance is two-fold:

- a. The average gas exhaust velocity is reduced because of friction between the gas and the nozzle wall in the boundary layer.
- b. The effective area ratio of the nozzle is reduced by growth of the boundary layer. The thickness of the boundary layer is characterized by the displacement thickness, δ^* .

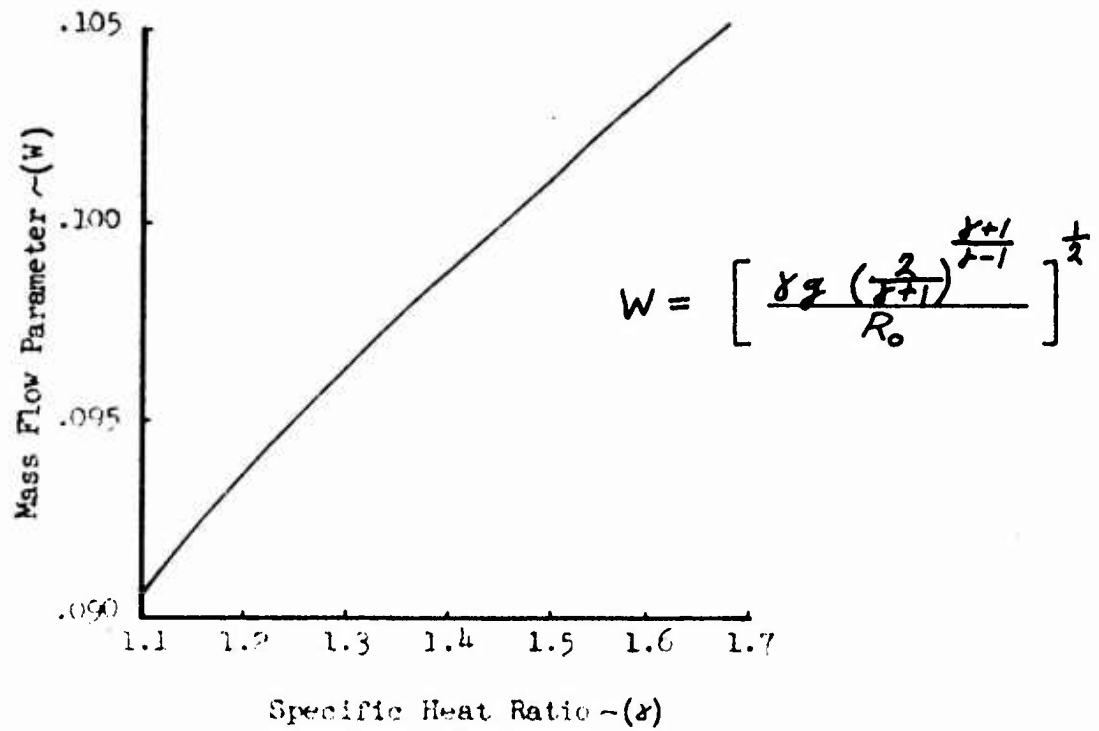


FIGURE 5.1-2 MASS FLOW PARAMETER

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Nozzle flow with a boundary layer is schematically illustrated below:

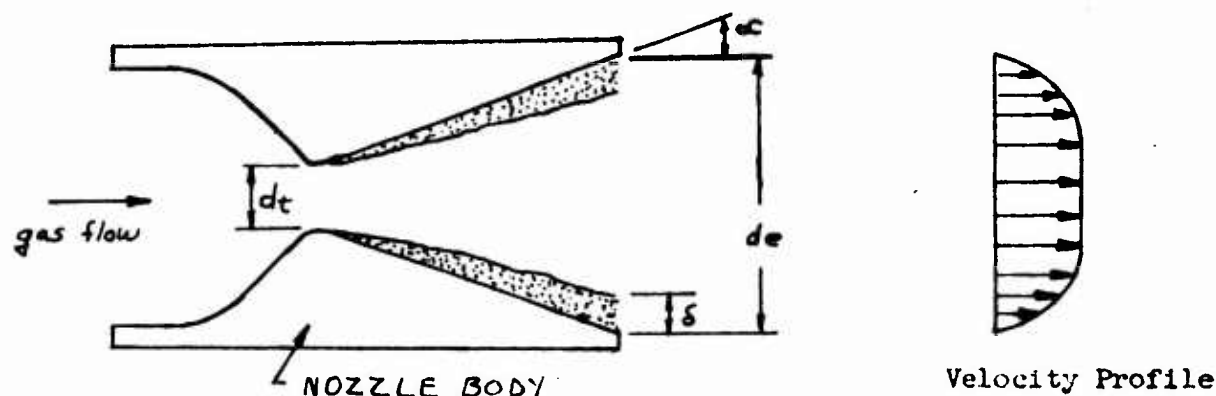


FIGURE 5.2-1 NOZZLE FLOW WITH A BOUNDARY LAYER

An estimate of nozzle performance can be obtained by calculating the boundary layer displacement thickness, and the total viscous drag force at the nozzle wall. For design purposes, the use of the correction factors C_V and C_D is most convenient. Values of C_V and C_D can be estimated from the experimental data summarized in Figures 5.2-2 and 5.2-3. The correction factors C_V and C_D are applied to the ideal performance factors in the following manner:

$$C_{F_{\text{actual}}} = \lambda C_{F_V} \cdot C_V \cdot C_D + C_{F_P} \quad (5.2-1)$$

$$\dot{M}_{\text{actual}} = \dot{M}_1 \cdot C_D \quad (5.2-2)$$

The pressure thrust coefficient, C_{F_P} , is a small part of the total thrust coefficient, being less than 2% of the total thrust coefficient for area ratios above approximately 50:1, at $\gamma = 1.4$. Therefore, the velocity, divergence, and discharge coefficients can be applied to the total ideal thrust coefficient, C_{F_1} , without significant error. That is:

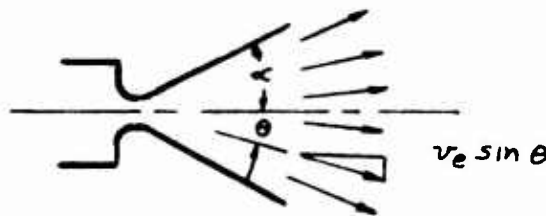
$$C_{F_{\text{actual}}} \approx \lambda C_{F_1} \cdot C_V \cdot C_D \quad (5.2-3)$$

The difference between ideal and actual nozzle performance is primarily the result of boundary layer effects, so the velocity and discharge coefficients are correlated by the throat Reynold's number, as shown in Figures 5.2-2 and 5.2-3. The throat Reynold's number is calculated from:

$$Re_t = \frac{\dot{m}}{(\mu \pi) / (4 d_t)} \quad (5.2-4)$$

5.2.2 DIVERGENCE ANGLE EFFECTS

The nozzle divergence correction is necessary because of the divergence of exit velocity vectors from the axial direction, represented below:



Although the velocity vectors have a magnitude equal to the ideal one-dimensional value v_{e_i} , the component $(v_e \sin \theta)$ produces no useful axial thrust. The correction factor for nozzle divergence is designated (λ) , and is evaluated as:

$$\lambda = 1/2 (1 + \cos \alpha) \quad (5.2-5)$$

where α is the nozzle divergence angle shown above. The divergence angle correction factor is applied to the velocity term in the thrust coefficient such that:

$$C_F = \lambda C_{F_V} + C_{F_P} \quad (5.2-6)$$

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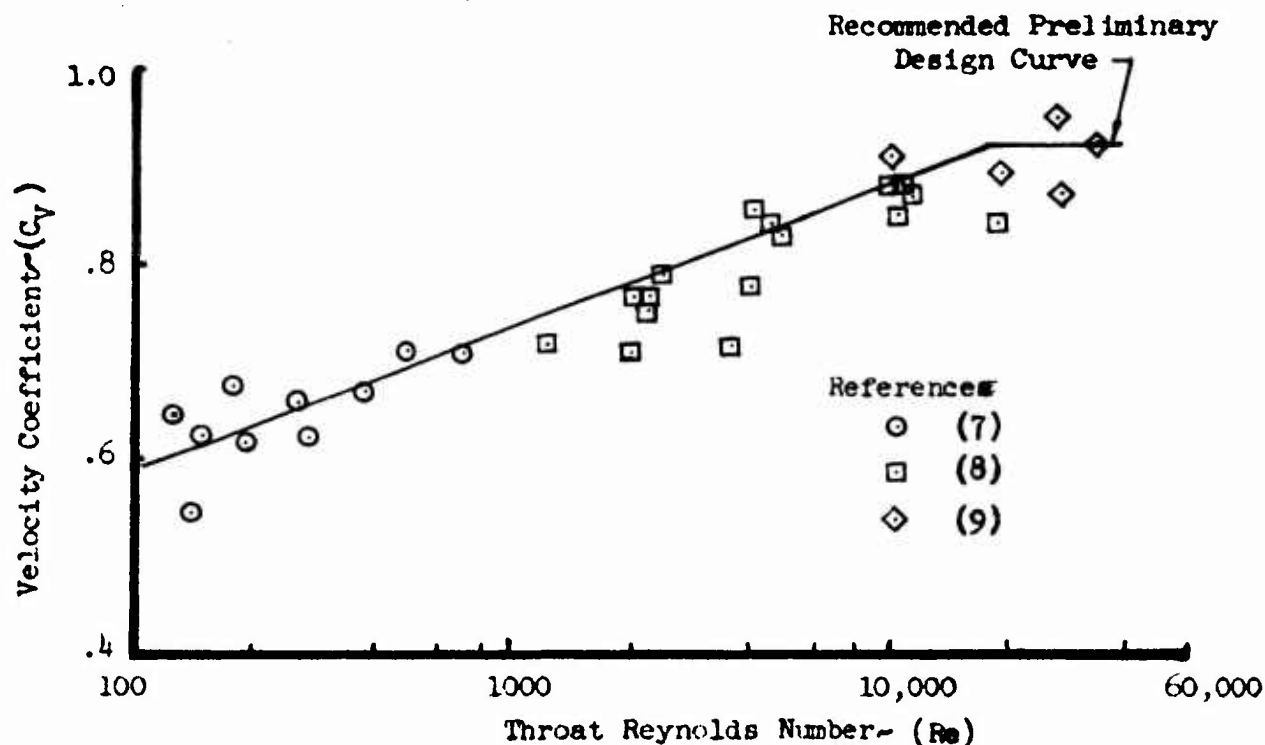


FIGURE 5.2-2 VELOCITY COEFFICIENT

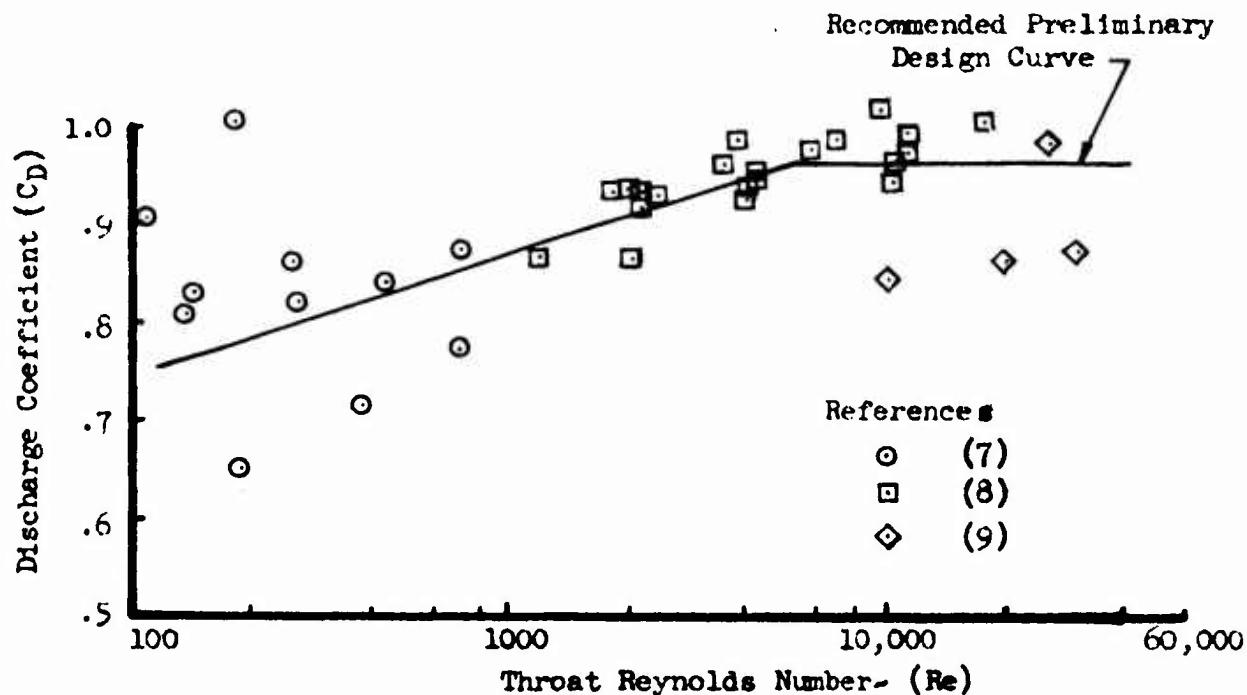


FIGURE 5.2-3 DISCHARGE COEFFICIENT

Figure 5.2-4 shows the effect of nozzle divergence angle, α , on thrust coefficient as a function of nozzle expansion ratio, and specific heat ratio, and divergence angle of conical nozzles.

5.2.3 PROPELLANT AND GAS EFFECTS

In the real case, actual performance also differs from "ideal" values because the propellants are not really homogenous, compositionally invariant and in chemical equilibrium throughout the chamber and nozzle. Monopropellant engines are reactors designed to change propellant condition by catalysis. This process permits propellants to exist in various conditions within the chamber. Additionally, dissociation may also follow this process, as with neat hydrazine (N_2H_4). Bipropellant engines are designed to promote chemical reaction of fuel and oxidizer within the chamber. Obviously, compositional variations exist throughout the mixing and chemical reaction process which, when related to time, represents different locations within the engine. Fuel rich flow is usually provided to cool the chamber walls. Also, recombination can accompany these processes. Since these effects are related to engine design they will be discussed additionally under the particular engine involved.

Certain propellants contain water vapor as an exhaust product. Vapor condensation has been suggested as a source of performance variations from that calculated for "ideal" conditions. However, condensation effects on nozzle performance cannot now be predicted with confidence in view of the uncertainties involved in experimental efforts conducted so far. Further elaboration on this subject is available in References 7, 9 and 10. Until this effect is resolved, it is recommended that the magnitude of condensation effects be neglected in performance estimates.

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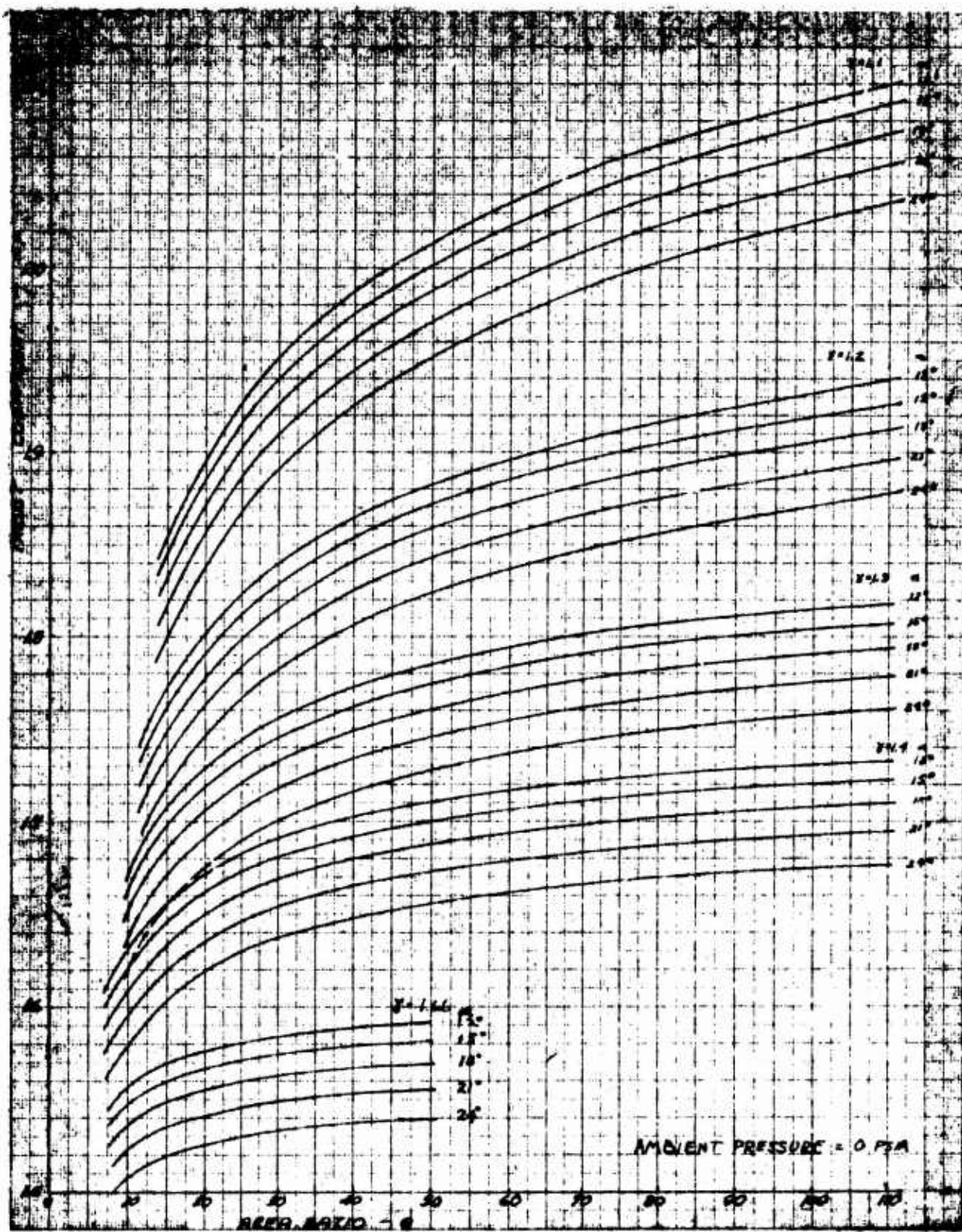


Figure 5.2-4 DIVERGENCE ANGLE EFFECTS ON THRUST COEFFICIENT

5.3 TRANSIENT PERFORMANCE

An analytical procedure is presented herein for determining transient performance, based on the analysis and experiments of Greer and Griep (Reference 9) and assuming

- 1) Constant density flow thru the valve orifice occurs
- 2) Choked flow at both the valve orifice and the thruster throat
- 3) Instantaneous valve opening at $\theta = 0$.

The following expressions for the pressure rise and decay transients are obtained:

$$\frac{P_c}{P_{ss}} = 1 - (y_0 + B)e^{-\tau} + B(y_0 + e)e^{-\tau} - e^2 \quad (5.2-7)$$

(rise)

$$\frac{P_c}{P_{ss}} = \left[1 - a_2(1 - \delta)e \right]^{\frac{2\delta}{1-\delta}} \quad (5.2-8)$$

(decay)

where

P_c = instantaneous chamber pressure

P_{ss} = steady-state, plenum chamber pressure

$$y_0 = \left[1 - P_0/P_{ss} \right]^{\frac{\gamma}{\gamma-1}} = 1 \text{ for vacuum operation} \quad (5.2-9)$$

$$B = \frac{A_o}{A_t} \left(\frac{\gamma}{\delta} \right)^{\frac{\gamma}{\gamma-1}} \left(\frac{\delta+1}{2} \right)^{\frac{\gamma}{2(\gamma-1)}} \quad (5.2-10)$$

τ = dimensionless time factor

$$= \theta \frac{A_t a^*}{2V_c} \left[\frac{2}{\gamma+1} \right]^{\frac{\gamma}{2(\gamma-1)}} \quad (5.2-11)$$

a^* = sonic velocity

δ = specific heat ratio

θ = time

A_t = nozzle throat area

A_o = valve orifice flow area

V_c = volume of thruster plenum chamber

The thruster rise time, neglecting valve transient effects, is the time required to reach $P_c/P_{ss} = 1$, or,

$$\Theta_r = -\frac{B}{a_1} \ln \left[\frac{B}{y_c + B} \right] \quad (5.2-12)$$

The decay time required for the pressure to fall from P_{ss} to P_a , is

$$\Theta_d = \left[\left(\frac{P_a}{P_{ss}} \right)^{\frac{1-\gamma}{2\gamma}} - 1 \right] \left(\frac{1}{a_2(\gamma-1)} \right) \quad (5.2-13)$$

where

$$a_1 = \frac{A_c a^*}{2V_c} \left(\frac{2}{\gamma} \right)^{1/\gamma} \quad (5.2-14)$$

$$a_2 = \frac{A_t a^*}{2V_c} \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{2(\gamma-1)}} \quad (5.2-15)$$

The preceding equations show that the thruster rise and decay times can be decreased by:

- 1) minimizing the plenum chamber volume, V_c
- 2) making the valve orifice area, A_o , large compared to the nozzle throat area, A_t .

Note that this analysis does not include the effects of a finite valve opening time, or the effects of electrical delays between application of an opening command and motion of the valve poppet. For well-designed thrusters, these delays are of the same magnitude as the thruster pneumatic delays. As a result, the transient response analysis must include the valve characteristics as well as the thrust characteristics.

6.0 THRUSTORS FOR LOW ΔV APPLICATIONS

6.1 COLD GAS THRUSTORS

6.1.1 GENERAL

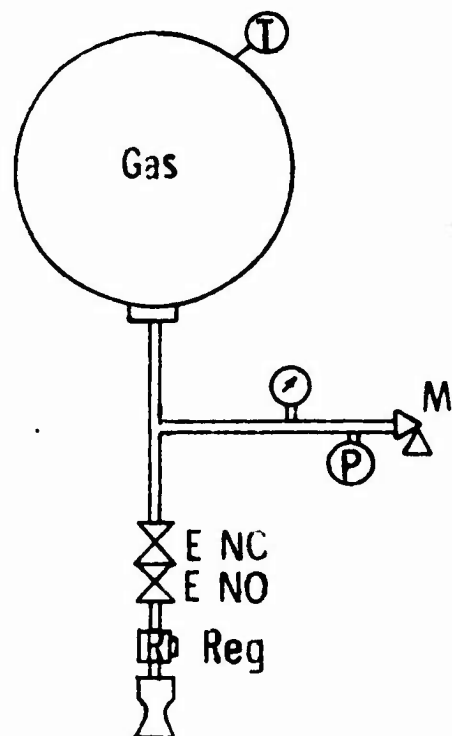
"Cold" gas propulsion systems (Figure 6.1-1) are popular, state-of-the-art systems drawing from a large variety of space-qualified, "off-the-shelf" hardware. Such new component development as is necessary for particular applications involves minimum development time and expense. These systems are relatively simple, reliable, low cost and easy to develop items which still deliver adequate performance and very small, precise and repeatable impulse bits. The principal disadvantages of cold gas systems involve low specific impulse, hence high propellant weight, and relatively high storage system weight to store the propellant as a gas. Some weight reduction is possible by using propellants which are liquid at ambient conditions such as propane or ammonia.

Thrusters for cold gas systems are simple in design, consisting of a gas plenum chamber, nozzle, solenoid gas valve and an inlet line. Figure 6.1-2 shows a typical cold gas thruster of the type used with satisfactory results throughout the Lunar Orbiter program. The principal variation to this design involves mounting the plenum and nozzle in some installations in such a way that the thrust vector is at an angle with respect to the gas supply vector to the plenum.

6.1.2 PRINCIPLE OF OPERATION

Cold gas propulsion systems rely upon gases stored at higher than environmental pressures to produce thrust upon expansion through a plenum-nozzle arrangement. The gaseous propellant is usually stored in high pressure (3000 - 4000 psia) gas bottles at ambient conditions. They are thus

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- M Manual Fill Valve
- E Explosive valve
- Cold Gas Nozzle
- Reg Pressure Regulator
- P Pressure Transducer
- T Temperature Transducer
- N.O. Normally Open
- N.C. Normally Closed
- Visual Gage

FIGURE 6.1-1. TYPICAL COLD GAS SYSTEM

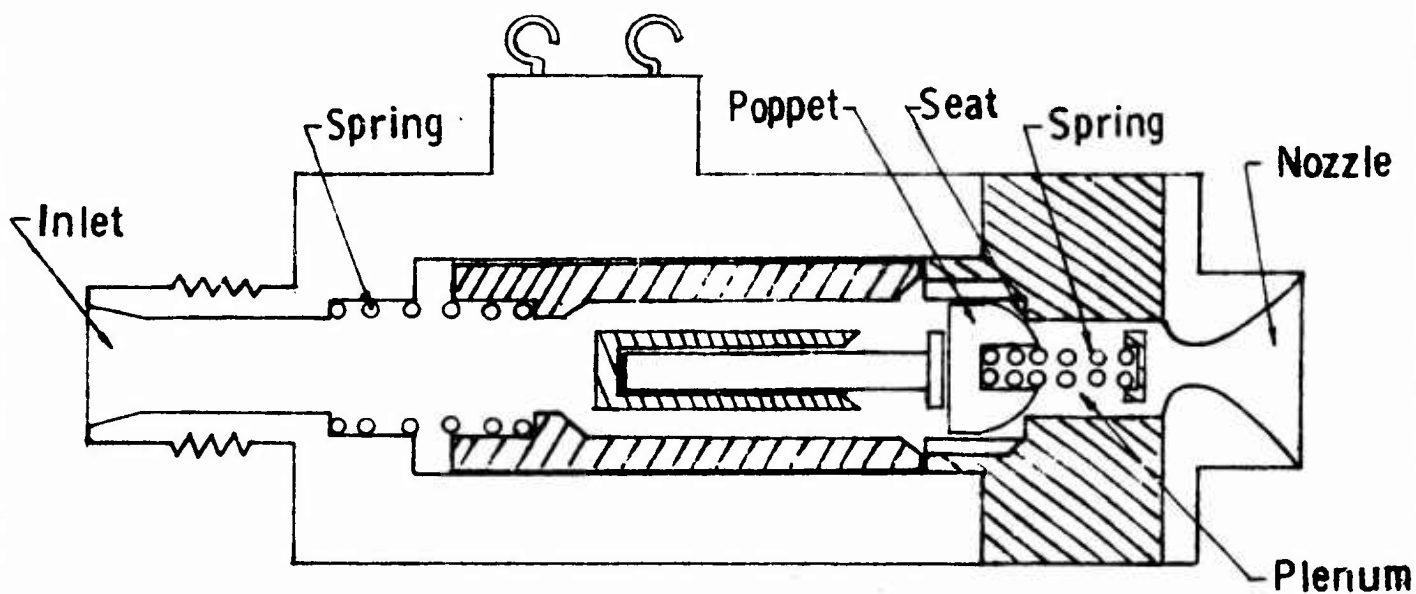


FIGURE 6.1-2. TYPICAL COLD GAS THRUSTOR

(Ref. 11)

referred to as "cold gas" systems, as opposed to "heated gas" systems in which thermal energy is added to the propellant prior to expansion.

In spacecraft, the gaseous propellant supply is generally isolated from the rest of the system, prior to operation, to allow servicing and checkout operations and to minimize propellant leakage. The system is activated by firing the isolation squib valves, providing propellant to the thruster valve inlet.

This is usually done prior to launch in the pre-launch or countdown sequence, or after reaching orbit. Cold gas systems are used infrequently in boosters, and then without isolation valving of the high pressure gas circuit.

The thruster valve controls gas flow, and consequently the impulse delivered by the engine. This valve is usually spring loaded so that failure of the power supply or solenoid coil causes the valve to fail in a closed position. In normal operation, an electrical command energizes the solenoid coil, moving the valve armature and lifting the valve poppet from the seat. This unblocks the valve exit, permitting gas to enter the plenum chamber. A smooth flow transition is provided to the nozzle entrance. The gas undergoes a controlled expansion in the nozzle, converting the random gas molecule velocity (measured by gas temperature) to an ordered exhaust velocity. The increase in mean gas velocity from essentially zero in the plenum chamber to the exhaust velocity at the nozzle exit produces a reaction force, or thrust. Additional thrust results from the pressure differential (nozzle exit pressure to ambient pressure) acting over the nozzle exit area.

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6.1.3 COLD GAS THRUSTOR CONSTRUCTION

The cold gas thruster is the simplest of small rocket engines, having only one propellant and requiring no catalyst. Figure 6.1-3 shows the construction of a typical unit involving a closely integrated valve and engine unit. Physically it consists of a nozzle, plenum chamber, and propellant control valve. The valve is predominant in cold gas thrusters, and especially so at lower thrust levels such as shown here.

Materials and construction methods are selected to satisfy the requirements for low cost, light weight, reliable systems having high cycle life and very low leakage characteristics. Shell and closure materials can be of high strength aluminum alloys, such as 2024, since thermal variations in the chamber are small. Attaching the nozzle assembly by means of mounting screws, as shown, makes it easy to change thrust level or nozzle expansion ratio by switching to nozzles with different throat and/or exit areas. This enables a single, basic unit to satisfy a range of thrust, expansion ratio, or geometry requirements, thereby reducing unit costs and development requirements.

The flow control unit consists of a hard, tungsten-carbide poppet and a stainless steel poppet seat. This assures a good gas seal for many operating cycles during prolonged exposure to the space environment. Internal and external leakage are reduced by providing teflon and silicon gaskets and by strongly loading the poppet seating spring.

6.1.4 COLD GAS PROPELLANTS

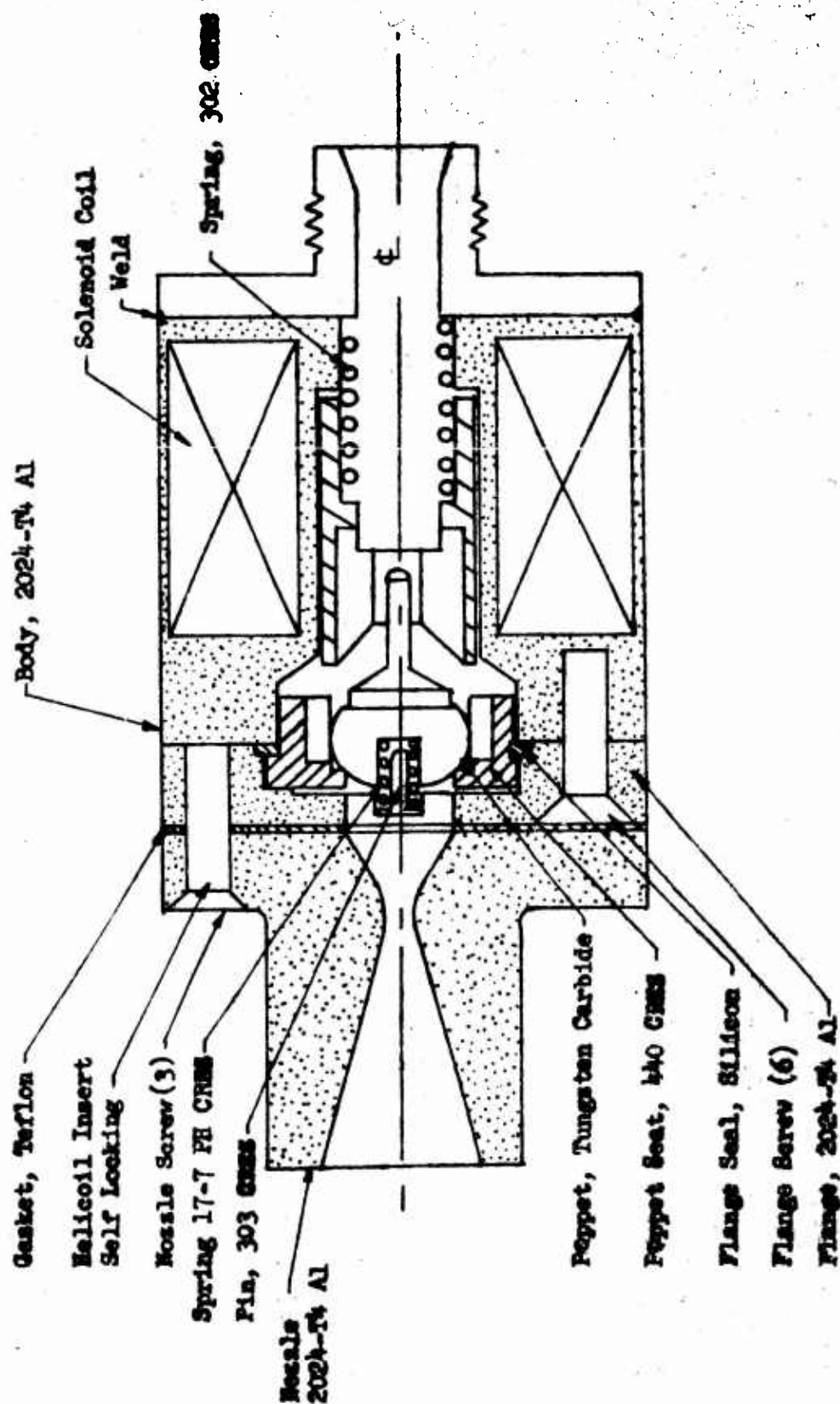
"Cold gas" thrusters used propellants stored in gaseous form at, or near, ambient conditions. They may also use gaseous propellants stored as liquids at reduced temperatures. They are referred to as "cold gas" thrusters primarily

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NUMBER 11-11A11A
REV LTR



(Refs. 12 and 13)

FIGURE 6.1-3 SOLID GAS VALVE - CONSTRUCTION DETAILS

to distinguish them from engines in which heating takes place by electrical, isotopic, or chemical means.

"Cold gas" thrusters have been operational for many years. During this period many different gases such as those in Table 6.1-1 have been suggested as candidate propellants. Primarily, they have consisted of single component gases, though some gas mixtures have also been considered. Generally, these gas mixtures occur as byproducts of other subsystems, such as for life support. Only single component gases are currently used, however, and among these, nitrogen applications predominate.

6.1.5 PERFORMANCE

Cold gas thruster performance may be rather easily determined on an ideal basis by use of expressions 5.1-19 through 5.1-27. This involves an assumption that the specific heat ratio (γ) is constant during expansion. This is a valid assumption since pressure and temperature effects are small enough to be neglected with most propellants. Hydrogen gas is an exception in this case. These performance expressions also require assumptions for nozzle expansion ratio and chamber operating pressure and temperature. These latter two items (chamber pressure and temperature) do not remain constant when the system uses an unregulated blowdown mode. In fact, gas storage temperature is not constant during pressure regulated operation, either, due to gas expansion in the storage bottle.

Theoretical performance of selected cold gas propellants is shown in Figure 6.1-4. However, in preliminary design exercises, steady state performance of cold gas propellants is not usually estimated from this data even if efficiency

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TABLE 6.1-1

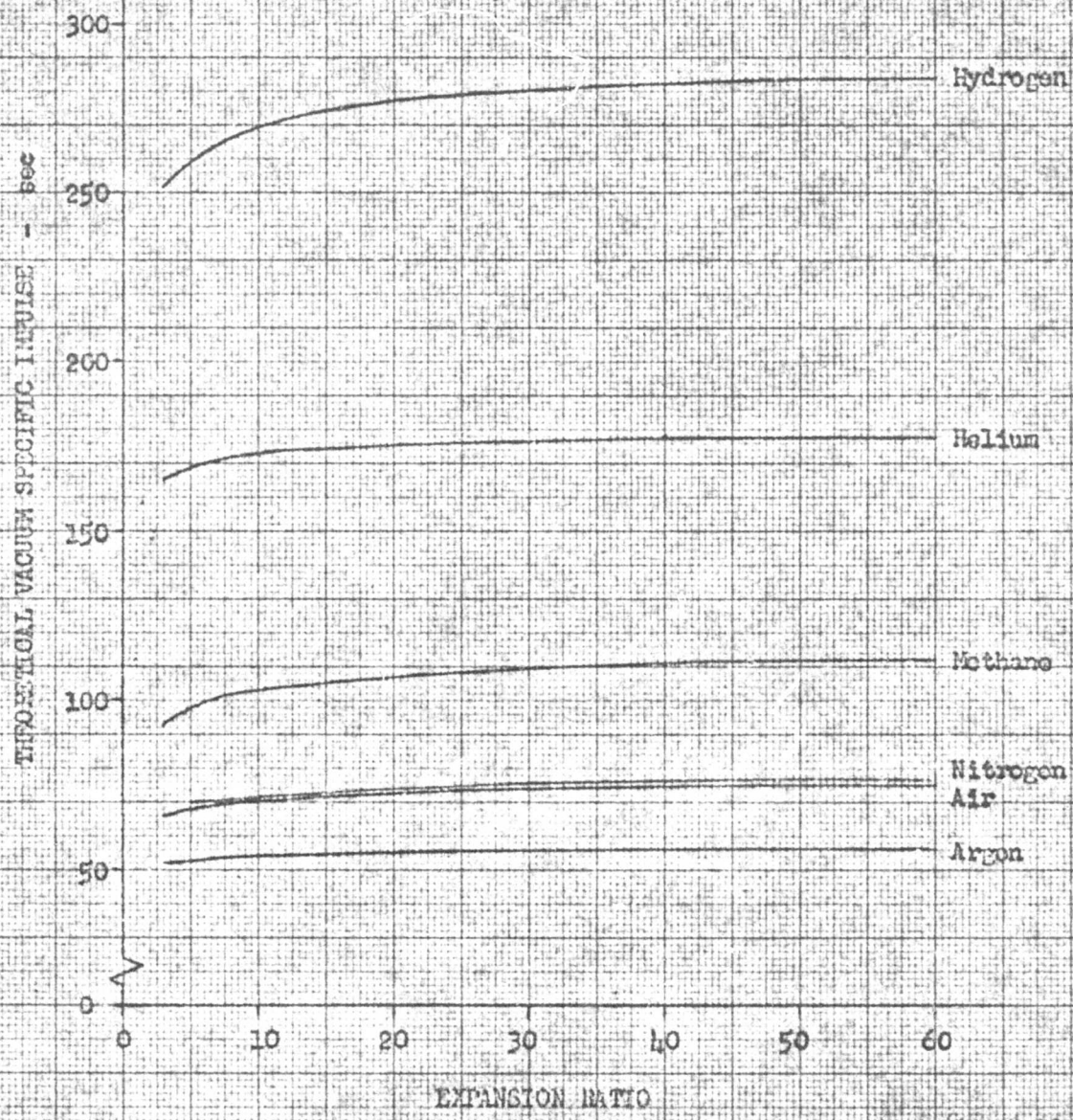
CHARACTERISTICS OF SINGLE COMPONENT COLD GAS PROPELLANTS

| Name | Symbol | Molecular Weight | Normal Boiling Point (°F) | Specific Heat Ratio, $(\gamma = C_p/C_v)$ | Max I_{sp} Theo ($@ 530^\circ R$) | Critical Temp. Press. | Critical Properties |
|----------------|------------|------------------|---------------------------|---|---------------------------------------|-----------------------|---------------------|
| Acetylene | C_2H_2 | 36.04 | -118.5 (sublimes) | to 26 @ 59°F | 97 | 96.8°F | 911 PSIA |
| Ammonia | NH_3 | 17.024 | -28 | 1.31 @ 59°F | 112 | 270 | 1639 |
| Argon | A | 39.944 | -302.55 | 1.67 @ 70°F | 56 | -188 | 705 |
| Carbon Dioxide | CO_2 | 44.01 | -109 (Sublimes) | 1.304 @ 59°F | 70 | 88 | 1072 |
| Ethane | C_2H_6 | 30.07 | -127 | 1.22 @ 59°F | 97 | 90 | 717 |
| Freon 11 | CCl_3F | 131.38 | +75.4 | 1.135 | 56 | 386 | 612 |
| Freon 12 | CCl_2F_2 | 120.9 | -18 | 1.138 | 59 | 233 | 580 |
| Freon 13 | $CClF_3$ | 104.47 | | 1.172 @ -22°F | 58 | 839 | 561 |
| Freon 14 | CF_4 | 88.01 | | 1.2 | 59 | -49.9 | 542 |
| Freon 21 | $CHCl_2F$ | 102.93 | +48 | 1.12 | 68 | 353 | 750 |
| Freon 22 | $CHClF_2$ | 86.48 | -41 | 1.178 @ 250°F | 62 | 205 | 716 |
| Helium | He | 4.003 | -452.06 | 1.66 @ 70°F | 179 | -450 | 33.2 |
| Hydrogen | H_2 | 2.016 | -423 | 1.41 @ 70°F | 295 | -400 | 188 |
| Methane | CH_4 | 16.04 | -258.5 | 1.31 @ 59°F | 116 | -117 | 674 |
| Nitrogen | N_2 | 28.016 | -320.45 | 1.40 @ 70°F | 80 | -233 | 493 |

(Ref. 14)

Notes:

Fluid Temperature is 530°R
Vacuum Expansion



(Ref. 4) *

| | | | | |
|-------|--|--|---------|------|
| CALC | | | REVISED | DATE |
| CHECK | | | | |
| APR | | | | |
| APR | | | | |

THEORETICAL PERFORMANCE
COLD GAS FLUIDS

THE BOEING COMPANY

FIGURE
6.1-4

PAGE
54

factors are available. Rather, it is arbitrarily specified as 68 lb_f-sec/lbm for nitrogen consistent with a +80°F to -40°F blowdown temperature range.

This procedure has developed from numerous designs, studies and applications conducted throughout the industry. It is also not uncommon to supplement this with a propellant loading based on safety factors between 2.0 and 3.0. In other words, industry experience with nitrogen systems in a variety of applications has produced a relatively conservative, but constant, value of 68 lb_f-sec/lbm for use in preliminary subsystem design. Nitrogen, being easily the most popular "cold gas" propellant has also developed into somewhat of a standard in that performance of other gases may be estimated by comparison. For example, the "ideal" performance equation:

$$I_{sp} = \frac{C_{FI}}{W} \sqrt{\frac{T_c}{m}} \quad (5.1-25)$$

can be further simplified to:

$$I_{sp} \approx K_G \sqrt{\frac{T_c}{m}} \quad (6.1-1)$$

where: K_G = a constant for a particular gas at specified conditions

Hence, the specific impulse of any other gas, I_{s_x} , equals:

$$I_{s_x} = I_{s_{N_2}} \left(\frac{K_x}{K_{N_2}} \right) \left[\frac{T_{c_x} m_{N_2}}{T_{c_{N_2}} m_x} \right]^{1/2} \quad (6.1-2)$$

or,

$$I_{s_x} = I_{s_{N_2}} \left(\frac{C_{F_x}}{C_{F_{N_2}}} \right) \left(\frac{W_{N_2}}{W_x} \right) \left[\frac{T_{c_x} m_{N_2}}{T_{c_{N_2}} m_x} \right] \quad (6.1-3)$$

On this basis, helium yields a steady state specific impulse of 158 lb_f-sec/lbm at equivalent T_c values.

6.1.6 COLD GAS THRUSTOR DESIGN

Most cold gas thrusters are engine-valve arrangements combined in a single housing into which different size nozzles can be installed. Preliminary design of the cold gas thrust chamber and nozzle can be conducted in the following manner:

- 1) Assume engine thrust level, F
- 2) Determine propellant flow rate, \dot{w} , by:

$$\dot{w} = F/I_s \quad (6.1-4)$$

where: $I_s = 68 \text{ lb}_f \text{ sec/lb}_m$ for nitrogen

Calculate I_s for other propellants using equation 6.1-2

- 3) Determine C_F for the propellant from Figures 5.1-3, 5.2-5 or equations 5.1-19 through 5.1-22.
- 4) Assume chamber pressure equal to 40 psia for pulse operated engines or 150 psia for steady state operation. Structurally, any value less than 400-450 psia is usually possible. However, high chamber pressure needs a small nozzle throat which is sensitive to contamination and difficult to produce economically, within tolerances, below 0.01 inches. The 40 psia value is common for small attitude control engines. Steady state operation usually involves higher thrust levels permitting the higher chamber pressure suggested.
- 5) Calculate nozzle throat size by:

$$A_T = F/P_C C_F \quad (6.1-5)$$

- 6) Determine chamber volume, V_C , by:

$$V_C = L^* (A_t) \quad (6.1-6)$$

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where: L^* , chamber characteristic length is selected above a minimum of 10 inches to minimize inlet effects of gas flow into the chamber.

6.1.7 COLD GAS THRUSTOR GEOMETRY

The closely integrated valve-chamber design of most cold gas thrusters causes them to be dimensionally quite dependent on valve characteristics. These characteristics are quite dependent on the valve manufacturer's approach. The cold gas engine thrust chamber and nozzle, immediately adjacent to the valve pintle can be sized in a preliminary basis using the following procedure:

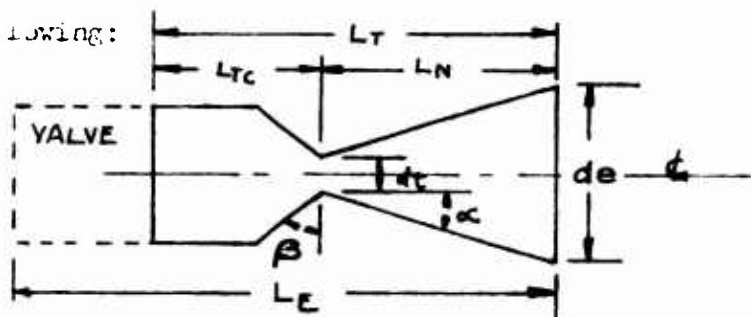
- 1) Assume, from 6.1.7, the following:

Chamber pressure (P_C)

Thrust (F)

Expansion ratio (ϵ)

Specific Impulse (I_s)



- 2) Assume the following values determined with the procedures described in 6.1.7:

Propellant flow rate, \dot{w}

Nozzle throat area, A_t

Chamber volume, V_C

- 3) Assume the following based on common practice with cold gas thrusters:

Nozzle divergence half angle, α , = 15° (conical)

Nozzle convergence angle, β = 30°

- 4) Determine nozzle exit area, A_e , thrust diameter, d_t , and exit diameter, d_e :

$$A_e = A_t \epsilon \quad (6.1-7)$$

$$d_t = \left[\frac{4A_t}{\pi} \right]^{1/2} \quad (6.1-8)$$

$$d_e = \left[\frac{4A_e}{\pi} \right]^{1/2} = d_t (\epsilon)^{1/2} \quad (6.1-9)$$

- 5) Calculate chamber length,
- L_{tC}
- , by:

$$L_{tC} = \frac{V_C + 0.398 d_t^3}{3.14 d_t^2} \quad (6.1-10)$$

- 6) Determine nozzle length,
- L_N
- , by

$$L_N = \frac{d_t \left[(\epsilon)^2 - 1 \right]}{0.536} \quad (6.1-11)$$

- 7) Determine thruster length,
- L_T
- , by

$$L_T = L_{tC} + L_N \quad (6.1-12)$$

6.1.8 COLD GAS THRUSTOR WEIGHT

Thruster weight is strongly affected by valve weight which in turn, depends on the valve manufacturer involved. Cold gas thrusters are usually basic units, sized for a range of thrust levels consistent with various nozzles and different propellant supply pressures. Hence, these units may be quite oversized on a weight basis at lower thrust ratings. That is, a lighter weight, more compact assembly might be developed if it were advisable from a weight and/or cost standpoint. However, cold gas thrusters are usually so small that they contribute little to total spacecraft weight. The total weight of cold gas thrust chamber, nozzle, and valve assembly may be estimated from the following expression:

$$W_{G.C.} = 0.2 + 0.15 F \quad (6.1-13)$$

This expression is reasonably valid within a thrust range of 0.05 to 30.0 lbs providing that an absolutely minimum weight package is not involved.

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6.1.9 DEVELOPED COLD GAS THRUSTORS

Cold gas thrusters have been developed for use over a thrust range of 0.002 to 14.0 lbs. Primarily they have used nitrogen or helium though Freon, krypton, and argon have also seen limited use. A list of these cold gas thrusters is shown in Table 6.1-2. This list implies a much greater number of thruster designs than actually exist. Cold gas thrusters are quite easily applied throughout a wide thrust level by varying inlet pressure and nozzle fittings. Thus, a few basic thruster/valve designs can easily cover a broad thrust range, providing structural design and response are adequate. Weight penalties associated with a large chamber pressure range are slight in the cold gas thruster sizes commonly employed. Response is very good since the cold gas valve and thrust chamber are very closely coupled. Thus, Table 6.1-2 includes both basic thruster designs and particular applications of these thrusters in which operating characteristics are somewhat different. This is an advantageous feature of cold gas thrusters in that development expenses can be written off against numerous programs. The units are relatively inexpensive on a recurring cost basis, and little development time is required for most programs.

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TABLE 6.1-2 DEVELOPED COLD GAS THRUSTORS

| THRUST (LBS) | PROGRAM | VENDOR | GAS | I _{sp} (SEC) | P _{in} (PSIA) | P _c (PSIA) | DIMENSIONS WITH VALVE (INCHES) | WEIGHT (LBS) | MIN. AMP SIZE | POWER (WATTS) |
|-----------------|--------------------------------|---------------------------|---------------------|--------------------------|---------------------------|--------------------------|--------------------------------------|-----------------|--------------------|------------------|
| | | | | | | | WIDTH LENGTH VALVE VALVE | | (LB-SEC) | |
| 0.0207 | DAO | | N ₂ | 74 | 14.3 7.0 | 5.0 | | 0.32 | | 2.0 |
| 0.05 | RANGER | STERER | N ₂ | 76 | | 15 | | | | |
| 0.02 | MARINER ROLL | STERER | N ₂ | 60 | 15 | | | | | |
| 0.028 | LUNAR ORBITER ROLL | STERER | N ₂ | 70 | 19 | | | 0.22 | | 4.5 |
| 0.03 | SURVEYOR | STERER | N ₂ | | | | | | | |
| 0.04 | MARINER PITCH, YAW | STERER | N ₂ | 60 | 15 | | | | | |
| 0.05 | ABLESTAR ROLL | | N ₂ | 74 | | | | | | |
| 0.05 | LUNAR ORBITER PITCH, YAW | STERER | N ₂ | 70 | 19 | | | .23 | | 4.5 |
| 0.05 | OGO A, B, C | TRW | ARGON | 56 | 50 | | | | | 6.5 |
| 0.05 | OGO-D | TRW | KRYPTON | 36 | 50 | | | | | 6.5 |
| 0.05 | OSO | | N ₂ | 66 | | 30 | | | | |
| 0.10 | OSO | | N ₂ | 66 | | 60 | | | | |
| 0.104 | DAO | | N ₂ | 74 | 14.3 7.0 | | 1.30 5.0 | .42 | | 28 |
| 0.20 | VASP | TRW | N ₂ | 72 | | | | | | 8 |
| 0.20 | VELA | TRW | N ₂ | 72 | 50 | | | | | 8 |
| 0.20 | PIONEER | TRW | N ₂ | 72 | 50 | | | | 4000 ⁻⁴ | 8 |
| 0.5- 0.2 | NIMBUS D | | FREON | 45 | 55 | | | | | |
| 1.0 0.1 | (WITH "C" NOZZLE) | JAMES, POND & CLARK | N ₂ , He | 65 ¹ 65 | 5- 50 | | 3.12 1.94 | .13 | | 5 |
| 1.0 | PAYLOAD AEROBEE | | He | | | | | | | |
| 2.0 | SYNCOM | | N ₂ | | | | | | | |
| 2.2 | BURNER II | KIDDET JP&C | N ₂ | 65 | | 150- 350 | 1.56 3.60 | | | |
| 2.5 | | STERER | N ₂ | | | | 1.97 3.08 | .563 | | |
| 2.5- 0.25 | (WITH "B" NOZZLE) | JAMES, POND & CLARK | N ₂ , He | 65 ¹ 65 | 5- 50 | | 3.12 1.94 | .13 | | 5 |
| 4.50 | ABLESTAR | | N ₂ | 74 | | | | | | |
| 4.0- 0.4 | (WITH "A" NOZZLE) | JAMES, POND & CLARK | N ₂ , He | 65 ¹ 65 | 5- 50 | | 3.12 1.94 | .13 | | 5 |
| 5.0 | | STERER | | | | | 2.26 4.13 | .563 | | |
| 5.0 | AEROBEE | | He | | | | | | | |
| 5.0- 1.0 | POLARIS STV | TRW | | 70 | 300 | | | | | 36 |
| 5.0 1.0 | ABLESTAR | | | 70 | 300 | | | | | 36 |
| 7.0 | DELTA- ROLL | | He | 160 | 345 | | | | | |
| 10.0 | | STERER | N ₂ | 120 | | | 2.78 5.06 | 1.67 | | 12 |
| 10. 0.5 | AGENA | STERER | N ₂ | 60 | 104.5 | 100 | 3.0 5.75 | 2.0 | | |
| 10.0 | | STERER | N ₂ | | | | 3.4 5.9 | | | 14.4 |
| 10.0 | AEROBEE | | He | | | | | | | |
| 12 | | STERER | N ₂ | | | | | | | |
| 13 | DELTA | | He | 160 | 345 | | | | | |

(Refs. 4 and 14)

6.2 HEATED GAS THRUSTERS

6.2.1 GENERAL

The disadvantages of cold gas thrusters related to their relatively low performance can be relieved by heating the gas. According to equation 5.1-25, specific impulse increases proportionally with the square root of gas temperature in the chamber, all other factors being equal. The currently popular cold gas systems are expected to be replaced in time with higher performance equipment which may include propellant heating provisions.

This section describes thrusters which are supplied with, and heat, a gas that is initially at ambient temperature. Thrusters supplied with a hot gas (e.g. from a main combustion chamber or gas generator) are omitted although portions of the performance data are applicable. Propellant gas heating is accomplished by using electrical resistance heaters (resistojets) or nuclear radioisotope decay (radioisojets).

6.2.2 PRINCIPLE OF OPERATION

A typical heated gas thruster consists of an inlet tube, a propellant valve, a heater, a heat exchanger, and a converging-diverging nozzle. The configuration is illustrated schematically on Figure 6.2-1.

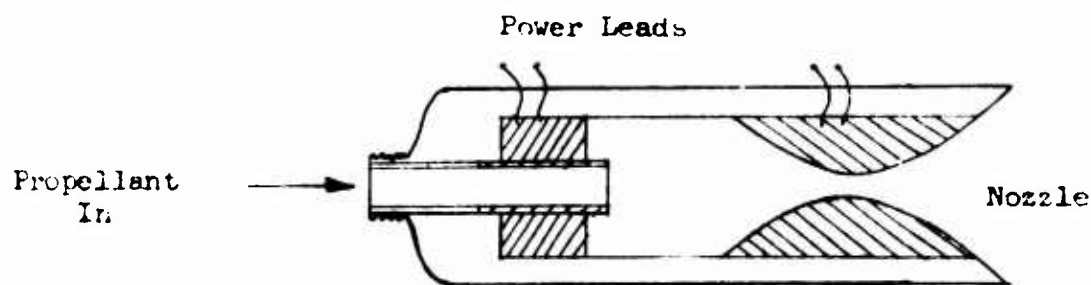


FIGURE 6.2-1 TYPICAL HEATED GAS THRUSTOR

This configuration has its own heater and heat exchanger unit, though several engines can be designed to use the same heater and heat exchanger.

Heated gas thrusters operate similarly to cold gas thrusters (6.1.2) except that the gas is heated prior to being exhausted through the nozzle. The heat exchanger is usually configured to raise gas temperature to some value between 1500°R and 4000°R.

A heated gas propulsion system can be designed identically to cold gas systems except for thruster differences. Thruster design includes a high temperature heater and, possibly, thermal insulation. Propellant storage, regulation, distribution and control systems are similar to cold gas systems. Thus, in the event of heater element failure the system can be used as a cold gas system.

Heated gas thrusters are designed as either "thermal storage" or "fast-heat up" devices. Thermal storage thrusters are primarily suited to pulse-mode applications, whereas the fast-heat-up thruster can be used in either pulse-mode or steady-state applications. Power, in the thermal storage thruster, is supplied continuously by a heater element (nuclear or electric) and propellant flow is pulsed. The applied power is equal to the thruster heat losses at the design operating temperature. The heat capacity of the thermal storage unit must be large enough for the heater element temperature to remain essentially constant during short propellant pulses. In the fast-heat-up thruster, both propellant flow and power are pulsed. In contrast to the thermal storage thruster, the heat capacity of the fast-heat-up device is minimized. As a result, the power input is equal to the thruster heat losses plus the heat required to increase the temperature of the propellant.

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The advantages and disadvantages of each of these concepts are summarized in Table 6.2-1

TABLE 6.2-1

COMPARISON OF HEATED GAS THRUSTOR CONCEPTS

| | Thermal Storage (High heat capacity) | Fast Heat Up (Low heat capacity) |
|---------------|--|---|
| Advantages | No thermal cycling Minimum response time Constant power input | Low average power consumption Low thruster weight constant Isp for all duty cycles |
| Disadvantages | Simple power supply High average power consumption High thruster weight Isp decreases as duty cycle increases | Frequent thermal cycling Delay between command signal and impulse bit More complex power supply |

Table 6.2-2 shows a list of applications of resistojets type heated gas thrusters.

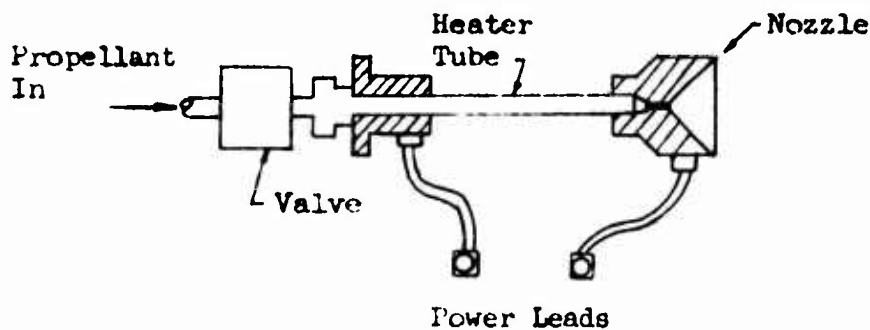
TABLE 6.2-2

RESISTOJET APPLICATIONS

| Application | Thrust (lb) | Vendor |
|---------------|---|-------------|
| Vela II | 0.042 | TRW Systems |
| Advanced Vela | 0.020 | TRW Systems |
| ATS - 1 | 500×10^{-6} | AVCO |
| ATS - C | 100×10^{-6} , 10×10^{-6} | AVCO |
| LES - 7 | | |
| DODGE-M | 3×10^{-6} , 6×10^{-6} 200×10^{-6} | AVCO |
| R&D | 0.020 | G.E. |

6.2.3 CONSTRUCTION OF HEATED GAS THRUSTORS

A simple heated gas thruster (Figure 6.2-2) is basically a cold gas engine with a heater and heat exchanger unit. When several thrusters use a single heater unit, each thruster has its own valve.



(Ref. 15)

LOW HEAT CAPACITY, FAST HEAT-UP HEATED GAS THRUSTOR
FIGURE 6.2-2

Propellant valves normally utilize cold-gas technology, such as elastomeric seals and valve seats, and therefore are thermally isolated from the high-temperature heat exchanger. Thermal isolation is accomplished by placing a propellant supply tube having a thermal resistance between the valve and the heat exchanger. When thrust is required, the valve is opened and propellant flows through the heat exchanger and the nozzle. The heat exchanger raises the propellant gas temperature from ambient temperature (typically about 500°R) to a temperature in the range of 1500°R to 4000°R.

The heat exchanger can be as simple as an electrically heated tube through which propellant gas flows, or it can use a relatively complex multiple-pass configuration.

Figure 6.2-2 shows a low heat capacity, fast-heat-up type of thruster. The resistive heating element is the stainless steel propellant feed tube. This configuration is simple, small, and light, but it has relatively lower performance because the heat transfer process is not particularly efficient and

because the heat losses during operation are quite high.

Figure 6.2-3 is a low heat capacity, steady-state type of thruster, designed for high performance (above 800 seconds specific impulse) with hydrogen gas propellant. The use of regenerative cooling reduces the heat losses.

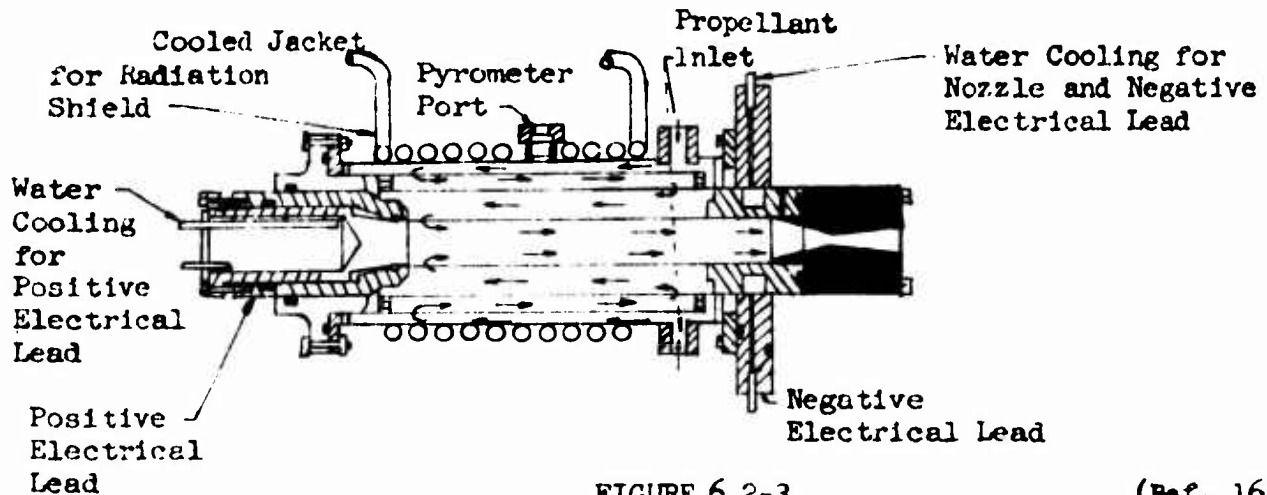
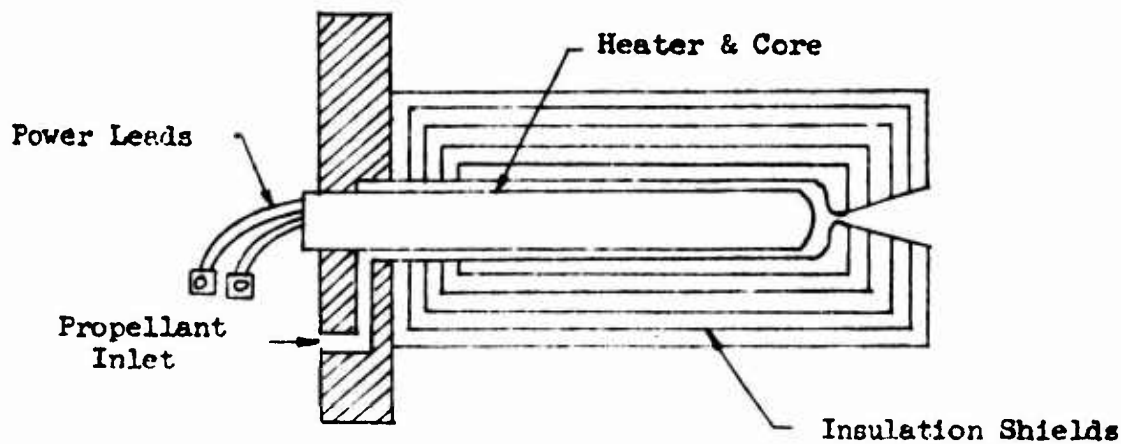


FIGURE 6.2-3

(Ref. 16)

WATER-COOLED TUBULAR HEAT EXCHANGER THRUSTOR

Figure 6.2-4 shows a high heat capacity thruster. The heater elements are mounted on a central core, which stores thermal energy when there is no propellant flow. When propellant is flowing, the central core is cooled as the propellant is heated. A radioisotope power core can be substituted for the resistance-heated core, if desired.



(Ref. 17)

FIGURE 6.2-4 HIGH HEAT CAPACITY HEATED GAS THRUSTOR

Insulation is used on thermal storage thrusters to reduce power requirements. It is not usually used with low heat capacity (fast heat-up) thrusters because (1) small thruster heat loss is low, (2) low thermal capacity is required, and (3) larger thrusters (i.e., hydrogen) can be regeneratively cooled.

Power requirements are significantly influenced by the impulse per pulse, and the number of nozzles per heater/core element. The maximum impulse per impulse bit and the duty cycle determine the required energy storage capacity and therefore determine the weight and volume of the core structure to be insulated. Each nozzle represents a "radiation window" in the insulation, so power required is affected by the number of nozzles. In addition, each nozzle requires a separate propellant feed line, so that the conduction component of the heat loss is dependent on the number of thrust nozzles used.

6.2.4 PROPELLANTS FOR HEATED GAS THRUSTORS

Propellants for heated gas thrusters include the single component gases nitrogen (N_2), helium (He), hydrogen (H_2), and ammonia (NH_3), as well as gas mixtures obtained from subliming solids such as ammonium sulfide $(NH_4)_2S$, ammonium carbonate $NH_4CO_2NH_4$ and ammonium hydrosulfide, NH_4HS . The VELA satellites used heated nitrogen (N_2) with 2% argon by volume.

Current emphasis is on the use of ammonia (NH_3) for smaller systems because of its high storage density (low storage volume) in liquid form. The advanced technology satellite (ATS-1) uses ammonia with a fast heat-up thruster. Advanced VELA is currently planned for ammonia, in conjunction with a thermal storage type thruster.

Previous emphasis on using hydrogen in high power systems ($\geq 1KW$) was based on the expectation that its potentially high specific impulse ($\approx 350 \text{ lb}_f \text{ sec}$) would offset the tankage penalties associated with its low density. This interest has recently abated in the absence of immediate missions and practical power supplies.

Characteristics of propellants seriously considered for use with heated gas thrusters are described in Table 6.1-1, since they are generally the same as those considered for cold gas systems.

6.2.5 HEATED GAS THRUSTOR PERFORMANCE

Estimates of steady state performance of heated gas thrusters can be made for preliminary design studies using the propellant performance data and procedures covered in 6.1.5 for cold gas thrusters. Basically, a broad range of performance is possible if enough power is available for raising gas temperature. Performance for nitrogen thrusters can thus be estimated by using:

$$I_{SP_{N_2}} = 3.32 \sqrt{T_c} \quad (6.2-1)$$

where: T_c = gas temperature in thrust chamber ($^{\circ}R$)

The performance of other gases can be estimated by modifying this expression to accommodate the difference in molecular weight, providing other processes such as dissociation are not involved. For other gases, equation 6.2-1 becomes:

$$I_{SP_x} \cong 17.58 \left[\frac{T_{cx}}{\bar{m}_x} \right]^{1/2} \quad (6.2-2)$$

where: \bar{m}_x = molecular weight

The principal differences from cold-gas thruster performance estimation concern dissociation effects with certain propellants such as ammonia. The effects of dissociation on performance evaluation are two-fold:

- a. Propellant chemical composition may change.
- b. The energy required to increase propellant temperature is significantly affected by the degree of propellant dissociation.

Figure 6.2-5 shows the effect of temperature and pressure on ammonia as it is progressively dissociated to nitrogen and hydrogen. The effect of dissociation on energy can also be inferred from this figure. It is thus shown, that after dissociation commences, large amounts of energy are absorbed by the dissociation process rather than by increases in gas temperature. For example, Figure 6.2-6 illustrates the effect of dissociation on specific impulse for two different thrusters designs having different surface-to-volume ratios

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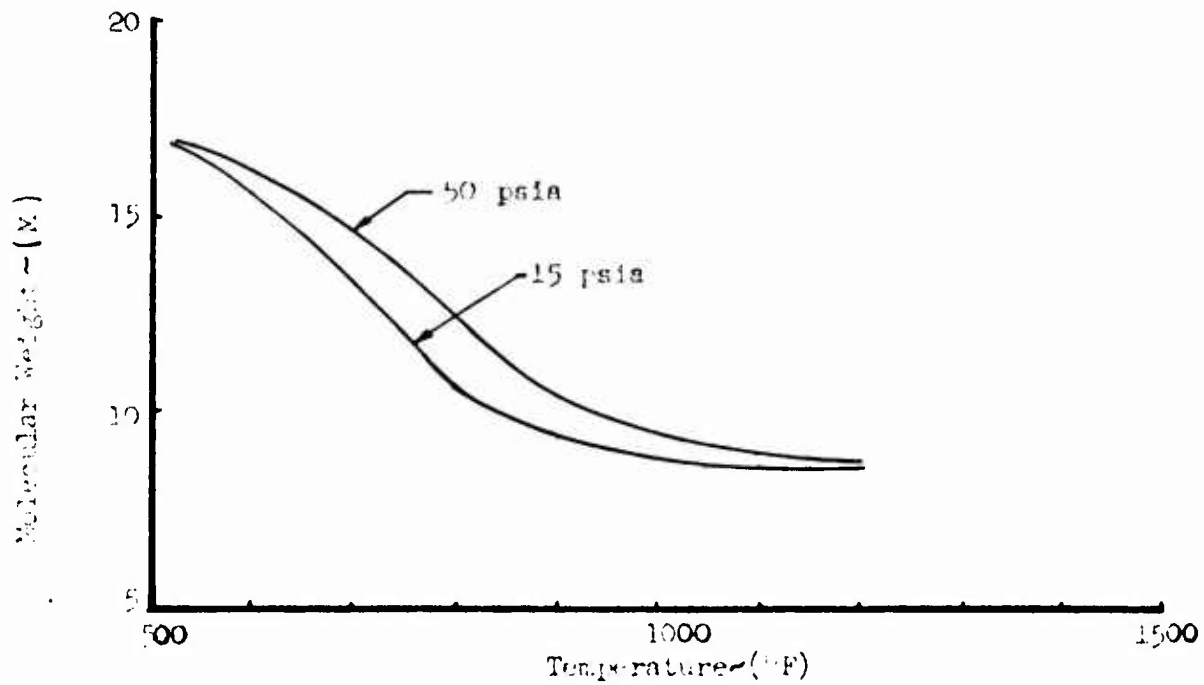


FIGURE 6.2-5 MOLECULAR WEIGHT OF THE EQUILIBRIUM
 $\text{NH}_3 = \text{N}_2 + 3\text{H}_2$ SYSTEM

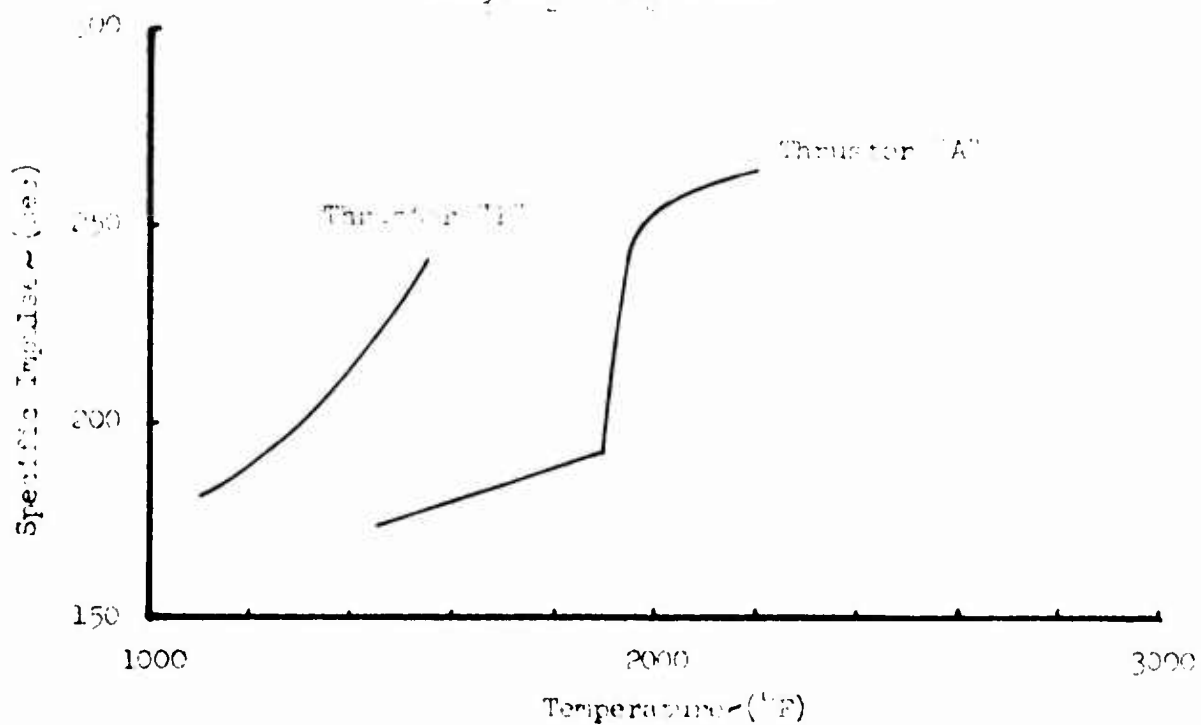


FIGURE 6.2-6 DISSOCIATION EFFECT ON PERFORMANCE OF
HEATED AMMONIA THRUSTERS

(Refs. 15 and 18)

in the flow passages. The larger relative surface area means that more of the ammonia flow is exposed to the catalytic action of the propellant flow tubes, and hence more complete dissociation is obtained.

In the low heat capacity thrusters, the principal efficiency factors used to measure performance are the frozen flow efficiency, η_F , and the overall engine efficiency, η_e . The frozen flow efficiency is the ratio of available thermal power to the total power put into the propellant. The term "frozen flow" is used since propellant composition is essentially frozen at stagnation conditions. This occurs at low thrust levels since short nozzles produce propellant residence times measured in microseconds (Reference 15). Frozen flow efficiency is evaluated by:

$$\eta_F = \frac{\dot{m} (H_O - H_F)}{\dot{m} H_O} \quad (6.2-3)$$

where:

H_O = stagnation enthalpy of propellant

H_F = enthalpy of dissociation or ionization

= $41526 \alpha E_i / \eta$ (Btu/lb)

α = degree of dissociation ($0 \leq \alpha \leq 1$)

E_i = dissociation potential (volts) of the propellant molecule

This definition of frozen flow efficiency assumes that propellant enthalpy at the nozzle exit, H_e , is much less than the stagnation enthalpy, H_O , and so can be neglected. Since dissociation lowers frozen flow efficiency, thruster operating conditions are selected to minimize dissociation when good performance is desired.

Overall engine efficiency, η_e , is the ratio of the jet power to input power or:

$$\eta_e = \eta_f \eta_p \eta_n \quad (6.2-4)$$

where:

η_f = frozen flow efficiency

η_p = heater efficiency

η_n = nozzle efficiency = c_v

Heater efficiency is difficult to define analytically since it depends on the efficiency of insulation (if any), the method of cooling the thruster (radiation or regenerative) and the efficiency of the heat transfer process between propellant and heater. Nozzle efficiency, η_n , is simply the nozzle velocity coefficient, c_v , defined in 5.2-1.

Overall engine efficiency is calculated from the basic definition,

$$\eta_e = \frac{P_j}{P_i} = \frac{\text{Jet Power}}{\text{Input Power}} \quad (6.2-5)$$

Jet power can be calculated from measurements of thrust and Isp by

$$P_j = .0218 \text{ Isp } F \quad (6.2-6)$$

Input power is electrical power plus effective power of the incoming propellant stream,

$$P_i = P_{\text{electrical}} + \dot{m} H_1 \quad (6.2-7)$$

The slope of the curve on Figure 6.2-7 is an indication of the engine efficiency (the lower the slope, the higher the efficiency). The curve also shows that more power per unit of thrust is required when the specific impulse is increased.

Power required as a function of operating temperature is shown on Figure 6.2-8 for a thermal storage type of electrical thruster.

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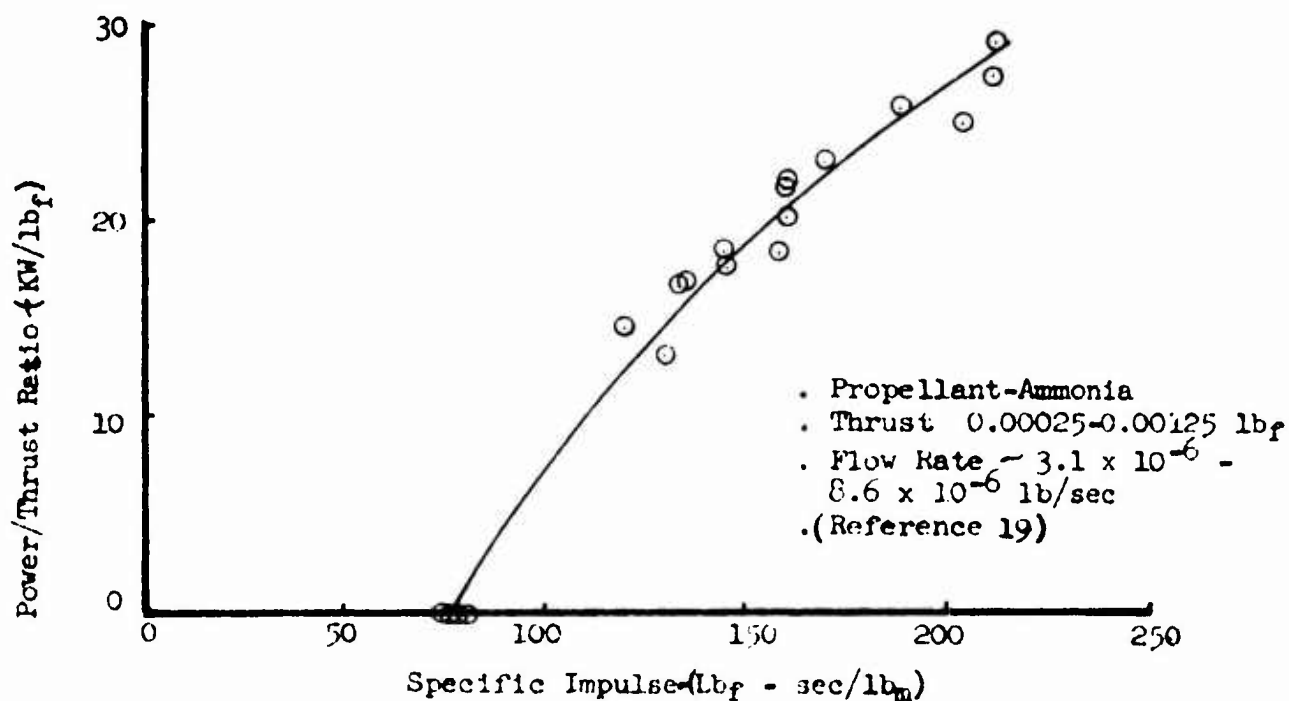


FIGURE 6.2-7 RESISTOJET POWER REQUIREMENTS,
FAST HEAT-UP THRUSTOR

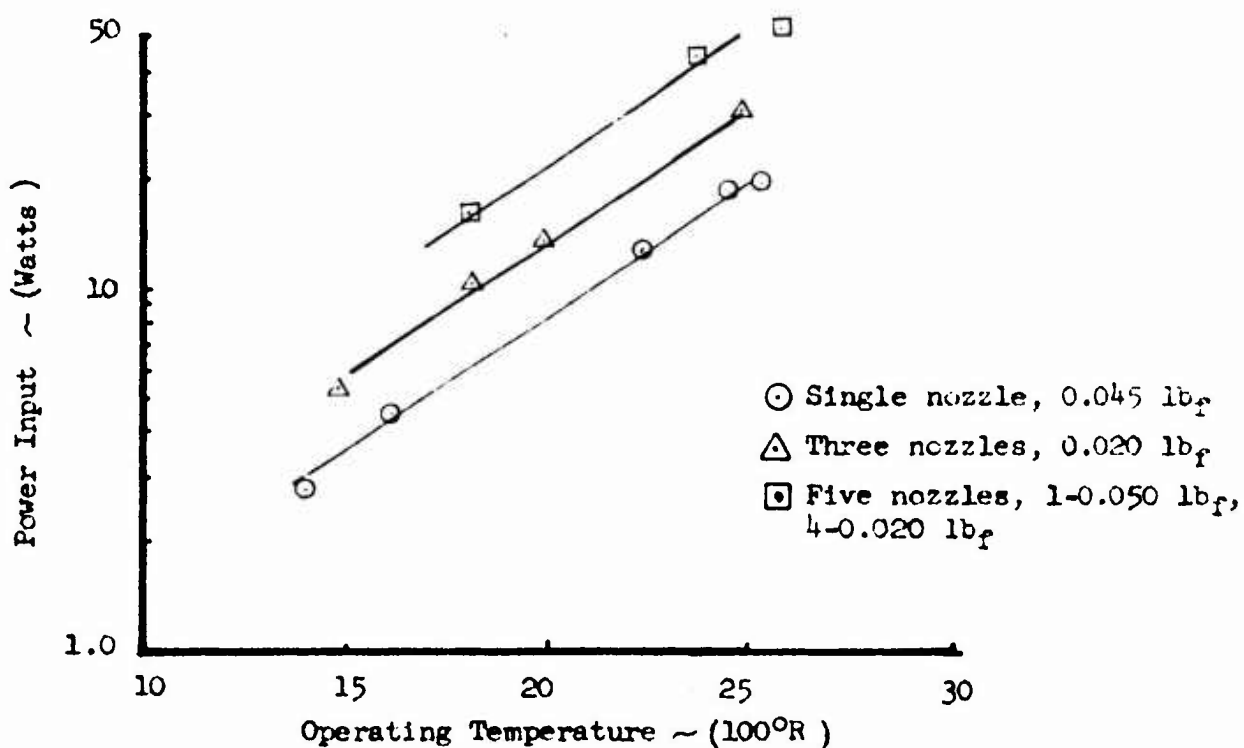


FIGURE 6.2-8 RESISTOJET POWER REQUIREMENTS,
THERMAL STORAGE THRUSTOR

For high heat capacity thrusters, the preceding efficiency factors, η_F , η_p , η_n do not adequately characterize the thruster performance. For example, maximizing the frozen flow efficiency means minimizing the degree of propellant dissociation. This occurs since additional electrical energy is required for propellant dissociation which is not then available during the expansion process. However, for high heat capacity thrusters, propellant dissociation does not require an increase in electrical power, so that the lower molecular weight of the dissociation propellant results in a performance increase with no increase in power requirements. As a result, a design goal for high heat capacity thrusters involves maximizing propellant dissociation at operating temperature and pressure.

6.2.6 DESIGN OF HEATED GAS THRUSTORS

Heated gas thrusters are basically cold gas thrusters which utilize gases at temperatures significantly above ambient conditions. The heater unit may be contained within the thruster, or remotely located. Consequently, the chamber design is similar to that required for cold gas thrusters except as it relates to heater, heat exchanger, and electrical provisions. Consequently, the following preliminary design procedure, similar to that suggested for cold gas thrusters, is presented:

- 1) Assume engine thrust level, F
- 2) Calculate propellant specific impulse, I_s , from:

$$I_{sp} = 17.58 \left[\frac{T_{c_x}}{\bar{m}_x} \right]^{\frac{1}{2}} \quad (6.2-2)$$

where: \bar{m}_x = molecular weight

- 3) Determine propellant flow rate by:

$$\dot{w} = F/I_{sp} \quad (5.1-23)$$

- 4) Determine C_F from Figures 5.1-3, 5.2-5, or equations 5.1-19 through 5.1-22.

- 5) Assume chamber pressure. Current practice involves chamber pressures between 1 to 30 psia, and usually between 7 to 20 psia. The real limiting condition is again that of manufacturing very small nozzle throats to close tolerances.

- 6) Calculate nozzle throat area by:

$$A_T = \frac{F}{P_c C_F \eta} \quad (6.1-5)$$

- 7) Determine free chamber volume, V_c , by:

$$V_c = L^* (A_t) \quad (6.1-6)$$

where: L^* - characteristic length is equal to a typical value somewhat greater than 10.

6.2.7 GEOMETRY

Figures 6.2-2 through 6.2-4 demonstrate that the physical size of heated gas thruster units considerably exceeds that of the basic chamber nozzle and valve. This additional space is occupied by the heater and heat exchanger unit which comprise most of the thruster. Since few actual thruster designs exist, insufficient dimensional information is currently available to develop general expressions for use in preliminary design.

6.2.8 HEATED GAS THRUSTOR WEIGHT

Heated gas thrusters are being considered in spacecraft preliminary design exercises with increasing frequency. However, thruster information suitable for preliminary design exercises has yet to be made available. Hence, this information must be inferred from the few designs extant. The weight of heated gas thrusters is strongly affected by thermal parameters, in addition to the usual engine design parameters of chamber pressure, specific impulse, thrust, and nozzle expansion ratio. Engine weight is particularly susceptible to duty cycle. The following expression is included for use in estimating the weight of heated gas thrusters. It has fair correlation to the few designs currently known. However, it is based on considerably fewer designs than was used to develop similar expressions for monopropellant and bipropellant engines. Nevertheless, it does appear to offer a reasonable solution to preliminary weight estimates for heated gas thrusters. Since these devices operate at very low thrust levels, and are thus quite small, the tolerances involved are probably not significant on a spacecraft weight basis. This expression is:

$$W_E = K_H [FI_s P]^{\frac{1}{2}} [0.33 + (P)^{1/3}] \quad (6.2-8)$$

where:

P = Engine total input power (watts)

K_H = A constant equal to 0.50 for all thermal storage engines, and for fast-heat-up engines above 0.0025 lbs thrust. Fast-heat-up engines below this value will have a K_H value defined by:

$$K_H = \frac{0.05}{[P]^{\frac{1}{2}}}$$

6.2.9 DEVELOPED HEATED GAS THRUSTORS

Heated gas thrusters have been developed from 10^{-6} to 0.4 lb thrust using nitrogen or hydrogen propellants heated electrically or by isotope radiation. Flight applications have so far been limited to an upper thrust level of approximately 0.04 pounds. Table 6.2-3 lists known details of these engines.

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TABLE 2-3 DEVELOPED HEATED GAS THRUSTORS

| THRUST PER NOZZLE | PROGRAM CONTRACT OR AGENCY | VENDOR | MODEL | NUMBER NOZZLES/ THRUSTOR | HEATUP TIME (MIN) | PROPELLANT | CHAMBER TEMP (°F) | I_{sp} (SEC) | P_c (PSIA) | P_{in} (PSIA) | P_{at} (ATM) | DIMENSIONS (INCHES) WIDTH LENGTH | WEIGHT (LBS) W/O VALVE | WITH VALVE | ELECTRICAL POWER (WATTS) VALVE HEATER | MINIMUM IMPULSE BIT I Min (LB SEC) | THR (SEL) |
|-------------------------|----------------------------------|--------|-----------|--------------------------------|-------------------------|---------------------------------|-------------------------|-------------------|-----------------|--------------------|-------------------|--|---------------------------|------------|---|---|-------------------|
| 1100 | | AVCO | | | | NH ₃ | | | | | | | | | | | |
| 3100 | | GE | | | | NH ₃ | | | | | | | | | | | |
| 6100 | DODGE M | GE | | | | H ₂ | | 650 | | | | | | | | | |
| 1100 | | AVCO | | | | NH ₃ | | | | | | | | | | | |
| 2100 | DODGE M | GE | | | | NH ₃ | | | | | | | | | | | |
| 5100 | ATS I | AVCO | | 1 | | NH ₃ | | | | | | | | | | | |
| 6100 | | AVCO | | | | NH ₃ | | | | | | | | | | | |
| 9100 | ATS B | TRW | | | | NH ₃ | | 150 | | | | | | | 10 | | |
| 0.1, 0.005 | USAF | TRW | DART | 4 | | NH ₃ | 1500-2000 | 240-280 | 15 | | 50 | 5.3** 6.0** | (CLASSIFIED) | | 5 | 155-150 1000 (PU/38) | 10 ⁻⁴ |
| 0.1, 0.005 | AEC | TRW | HRT | MULTI | | H ₂ | 1500-2000 | 485-585 | | | 50 | | 4.5 | | | (PU/38) | 10 ⁻⁴ |
| 0.045 | TEST | GE | | 5 | | NH ₃ | | | | | | | | | | | |
| 0.045 | TEST | GE | | | | H ₂ | 4500 | 260 | | | | | | | | | |
| 0.02 | TR&D | TRW | | | | NH ₃ | | | | | | | | | | | |
| 0.02 | TR&D | TRW | ACSKS | 4 | 30 | NH ₃ | 1550-1750 | 240-260 | 15 | | 50 | 5.0 9.7 | 0.40 | 0.50 | | 14 | 4100 ⁴ |
| 0.02 | ADV. VELA | TRW | ADV. VELA | 3 | 2 | N ₂ O ₂ A | 1250-1425 | 132 | 30 | 50 | 67** | 1.4** 2.9 | 0.50 | | | 17-30* | 4100 ⁴ |
| 0.02 | | GE | | | | NH ₃ | | | | | | | | | | | |
| 0.02 | NASA | GE | TSK-2000 | 1 | | NH ₃ | 1840-2100 | 228-266 | 22.5 | | | 2.0 5.0 | | 1.75 | | 30-37 | |
| 0.02 | GODDARD | GE | -1 P | | | NH ₃ | | 190 | | | | | | | | | |
| 0.02 | NASA | GE | | | | NH ₃ | 1180-1450 | 230 | | | | | | | | | |
| 0.042 | VELA III | TRW | VELA 3 | 1 | 5 | N ₂ O ₂ A | 1000-1200 | 123* | 15 | | 100 | 2.3** 5.1** | 0.65 | | | 60 ISOTOPE (PM147) | |
| 0.045 | AFFDL | GE | XR204-4 | 1 | | NH ₃ | 2000 | 230 | 30 | | | | 0.96 | | | 92** | SVC 4800 |
| 05-01 | | GE | | | | H ₂ | | | | | | | | | | | |
| 05-01 | | GE | | | | NH ₃ | | | | | | | | | | | |
| 05-015 | | GE | | | | NH ₃ | | | | | | | | | | | |
| 05-02 | NASA | GE | | 4 (02) 11 (05) | | NH ₃ | 1378-2085 | | | | | | | | | | |
| 07 | | TRW | | | | H ₂ | | | | | | | | | | 4100 ⁴ | |
| 0.10 | NASA | MARQT | | | | NH ₃ | 4080 | 360 | | | | | | | | 240 | |
| 0.10 | | MARQT | | | | H ₂ | 4080 | 740 | | | | | | | | 3000 | |
| 0.12 | NASA 4101 | AVCO | | | | H ₂ | 4400 | 838 | 34.7 | | | 3.4 6.2 | | | | 5000 | |
| 0.25 | POODLE | TRW | | 1 | | H ₂ | 3600 | 710* | | | | 7.4 17.0 | 45 | | | 15000 ISOTOPE (PO 210) | |
| 0.30 | | AVCO | 6-A | | | | | 150 | 14 | | | | | | | 10 | |
| 0.36 | | AVCO | 7-A | | | | | 150 | 14 | | | | | | | 10 | |

(Refs. 2, 14, 20 and 21)

6.3 MONOPROPELLANT THRUSTORS

6.3.1 GENERAL

Liquid monopropellant rocket engines produce thrust by catalytically decomposing certain chemically active propellants called monopropellants in a reactor and directing the exhaust through a plenum-nozzle arrangement. Monopropellant engines are used in Syncom, Scout, ATS, Apollo, Centaur, Titan III, Burner II and many other programs.

Early monopropellant engines used either ethylene oxide or low percentage (60 - 80%) hydrogen peroxide as propellants. Since then, 90% hydrogen peroxide has come into common use, because it has higher performance and greater density. Future generations of monopropellant engines will probably employ either 98% hydrogen peroxide (H_2O_2) or anhydrous hydrazine (N_2H_4). The 98% hydrogen peroxide thrusters are being developed as growth versions of hardware currently used with 90% peroxide. Overall gains from these modifications can be as much as 10% in performance and 1% in propellant density which is enough to justify the necessary development. Hydrazine (N_2H_4) monopropellant engines are currently becoming more popular. In their first real space applications, Ranger and Mariner, the hydrazine engines required an "oxidizer slug" to initiate the decomposition process. Subsequently, "spontaneous" catalysts have been developed which are able to initiate decomposition at ambient conditions, and sustain it. Predominant among these is the Shell 405 (Shell Development Company) spontaneous catalyst which has provided the impetus for further use of hydrazine systems. Hydrazine engines have a performance advantage over peroxide engine, with typical steady state I_s values of 235 seconds for hydrazine as opposed to

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160 seconds for 90% peroxide and possibly 180 seconds for 98% peroxide. However, peroxide is about 40% more dense than hydrazine so volume requirements of 90% peroxide systems and hydrazine systems are essentially comparable. The 98% peroxide systems have about a 10% volume advantage over hydrazine systems.

Peroxide systems are used where cost and availability is important and where more performance is wanted than can be obtained with cold gas systems. Peroxide systems are somewhat storage limited, however, in that peroxide is so active that storage for long periods should be either in high pressure containers or in vessels constructed of materials which are particularly nonreactive with peroxide. Either option raises flight system weight, tending to offset the performance advantage over cold gas and the cost advantage over hydrazine. Fewer compatibility problems exist with 98% peroxide. However, it decomposes at higher temperatures than does 90% peroxide, exceeding the structural limits of the standard catalyst. Hence, a high temperature spontaneous catalyst must be developed for use in 98% peroxide engines.

Both spontaneous and nonspontaneous catalysts are in use with hydrazine engines, so hydrazine engines are available for either pulse mode or steady-stage operation. Hydrazine has superior space storage characteristics, and is thus generally considered for missions requiring high performance, several operating cycles and extended space storage capability.

Growth versions of hydrazine systems are based primarily on mixing hydrazine (N_2H_4) with water to depress its freezing point and with

hydrazine nitrate ($N_2 H_5 NO_3$) to increase performance. The latter mixture substantially increases decomposition temperature to the extent that it exceeds the structural capability of 405 spontaneous catalyst. Current research is directed toward developing a spontaneous catalyst-binder combination suitable for use with hydrazine-hydrazine nitrate mixtures. Materials compatibility is also being researched for this propellant though it is not emphasized to the extent that the catalyst research is.

Proposals are occasionally made to use other monopropellants having significantly greater performance and better density characteristics. Generally, these monopropellants have considerable development work remaining. It is doubtful at this time whether the advanced monopropellants will be used to any extent before they are replaced by high energy bipropellants, resistojets and electrical thrusters. Hence, it may be that the very high energy monopropellant systems will attain only limited use.

6.3.2 OPERATING PRINCIPLE - MONOPROPELLANT ENGINES

Monopropellant engines resemble other rocket engines except as their operation relates to the propellant decomposition process. Figure 6.3-1 is a schematic of a typical pressure regulated monopropellant propulsion system. In this system the propellant is supplied at constant pressure to the inlet of the engine valve. Figure 6.3-2 shows a typical monopropellant thruster, consisting of a valve assembly, injector, plenum chamber, catalyst bed and nozzle assembly. The engine valve controls monopropellant flow to the injector and into the catalyst bed where it undergoes a decomposition reaction. The products of decomposition, dissociation and possibly any additional recombination which take place in the plenum chamber then exit through the nozzle, producing thrust.

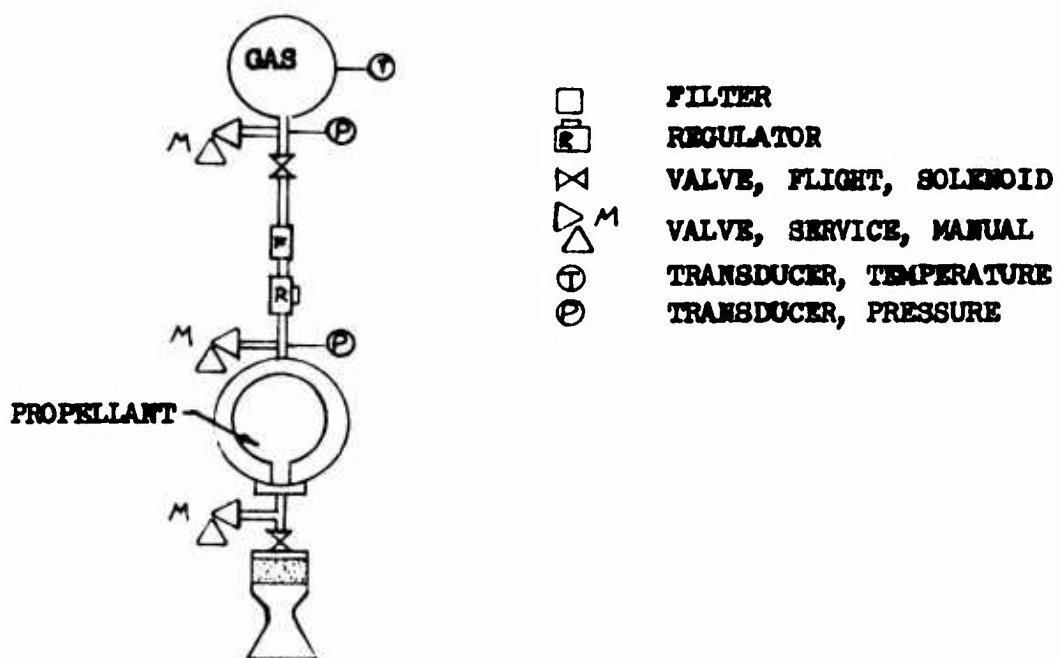


FIGURE 6.3-1 TYPICAL MONOPROPELLANT PROPULSION SYSTEM

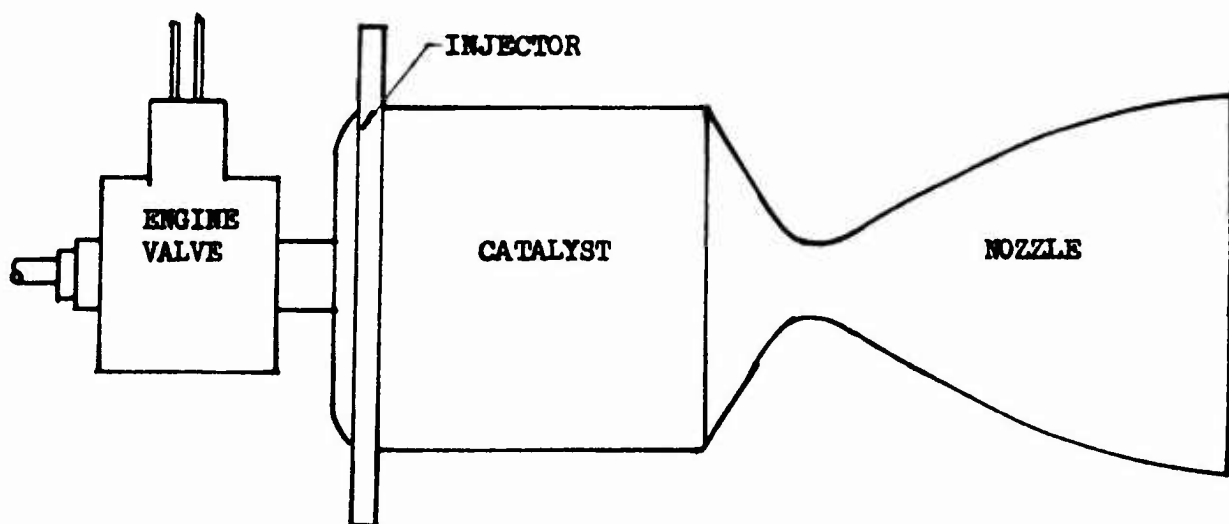


FIGURE 6.3-2 TYPICAL MONOPROPELLANT THRUSTOR

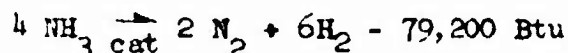
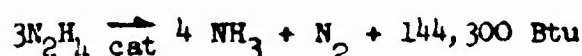
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6.3.2.1 HYDROGEN PEROXIDE ENGINE OPERATION

In monopropellant rocket engines, hydrogen peroxide is decomposed by passing it through a bed of stacked, silver alloy or silver-plated nickel screens in the thrust chamber. The decomposition process yields superheated water vapor and oxygen (O_2) gas. Decomposition gas temperature varies as a function of peroxide inlet temperature and thrust chamber pressure as shown in Figure 6.3-3.

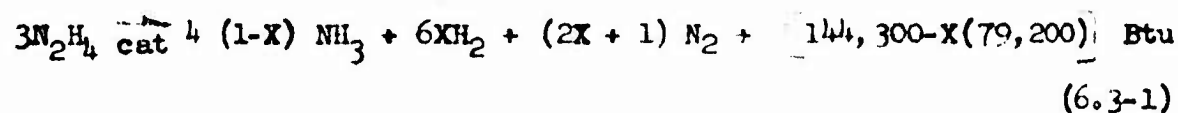
6.3.2.2 HYDRAZINE ENGINE OPERATION

Hydrazine, and hydrazine mixtures with water or hydrazinium nitrate, are decomposed by passing them through a bed of granules or small cylinders of a catalytic agent. Commonly the catalyst bed is located in the thrust chamber. Designs have been proposed in which the hydrazine is decomposed in a remotely located gas generator, the exhaust stored in a plenum chamber and thence directed to the thruster, as in Figure 6.3-4. The hydrazine decomposition process follows these consecutive reactions:



(where N_2H_4 and NH_3 are expressed in lb-mol)

Initially, hydrazine decomposition is exothermic, producing ammonia, nitrogen and heat. Ammonia dissociation, an endothermic process, follows, producing hydrogen and additional nitrogen and absorbing heat. Assuming that the initial reaction proceeds to completion, these reactions can be combined into a single equation related to the fraction of ammonia dissociation, X , as follows:



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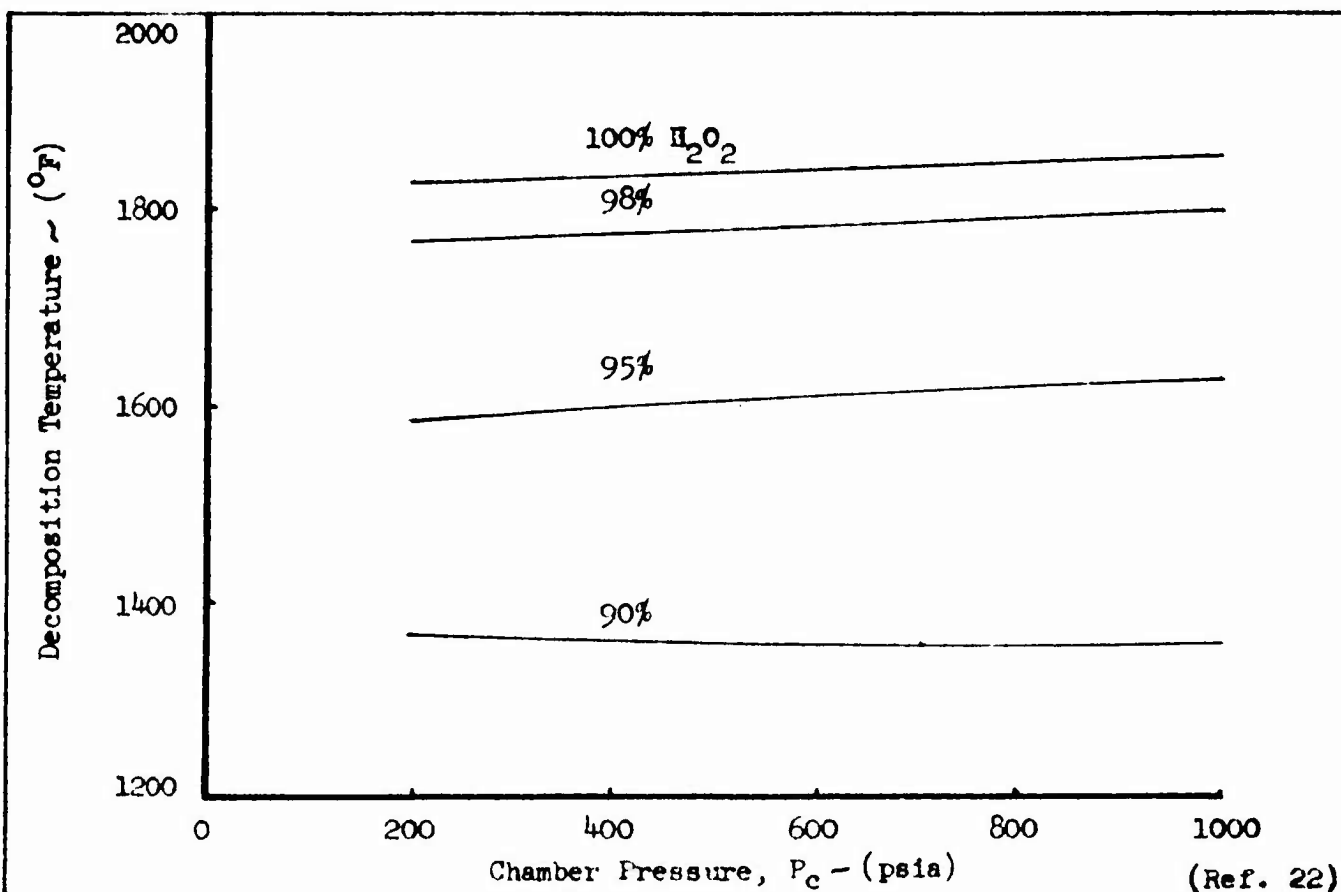


FIGURE 6.3-3 HYDROGEN PEROXIDE DECOMPOSITION TEMPERATURE

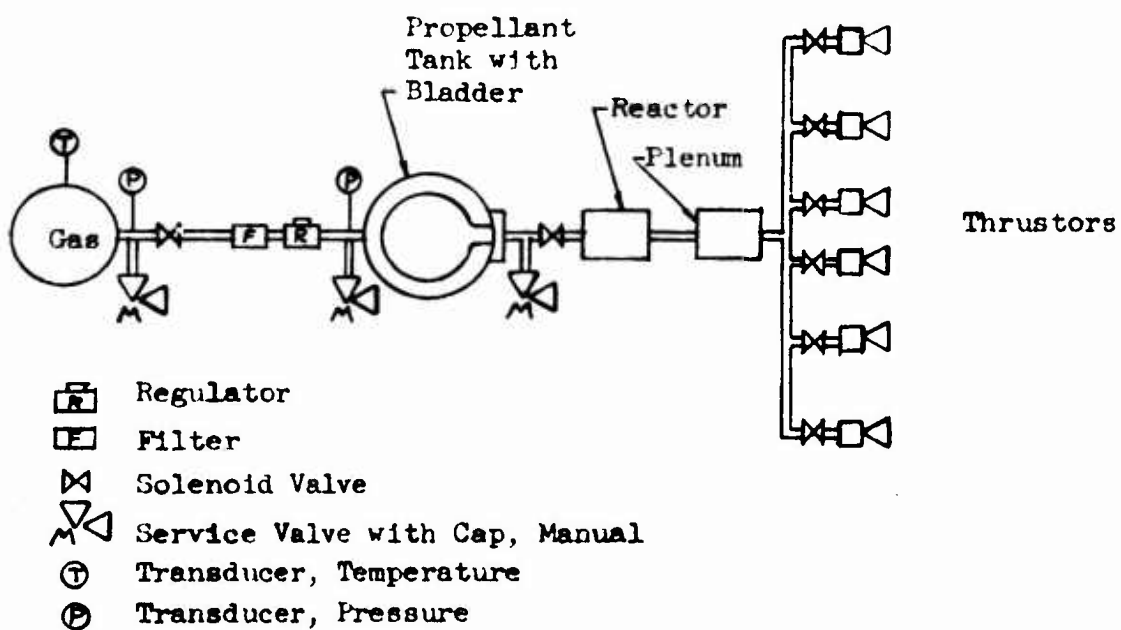
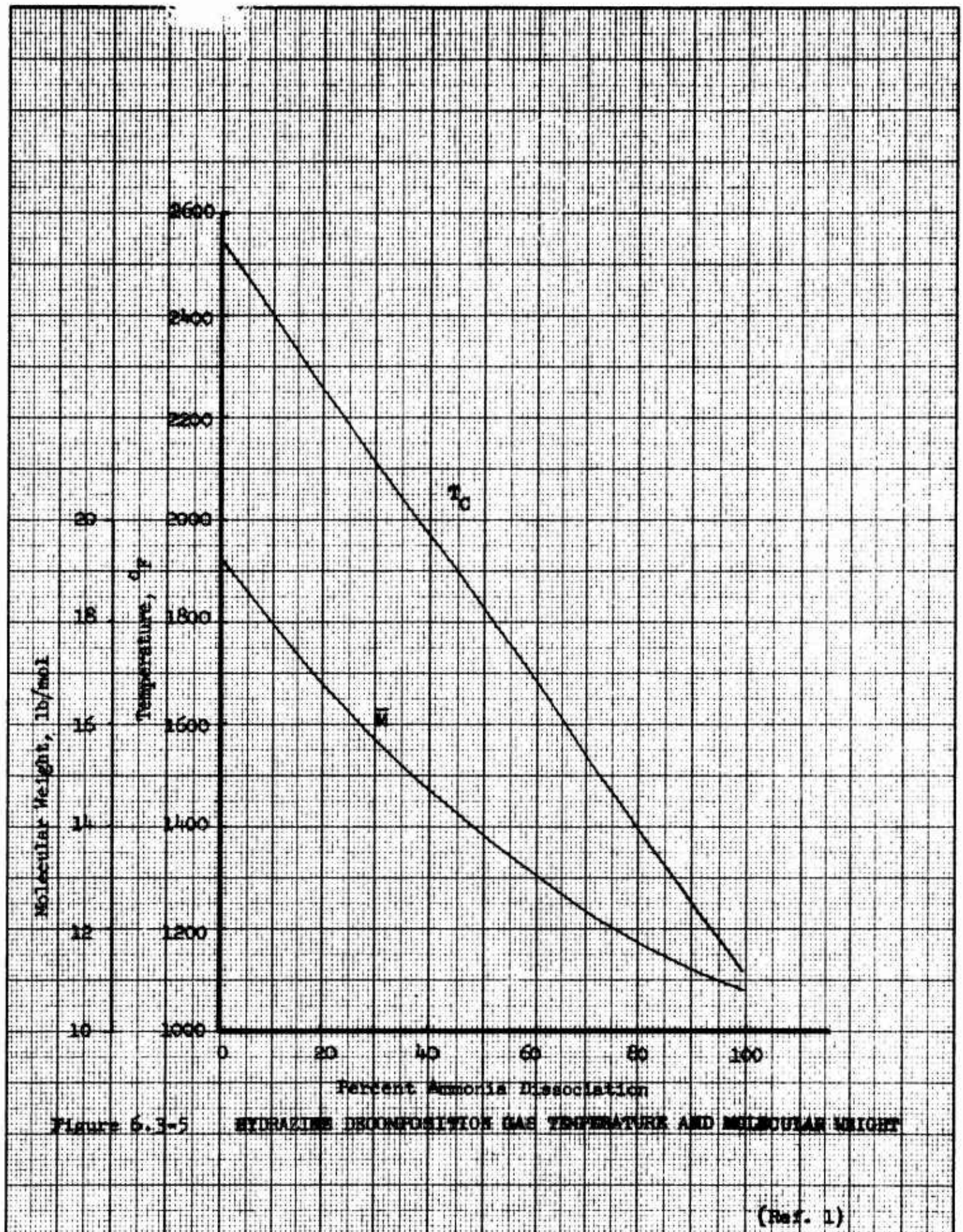


FIGURE 6.3-4 HYDRAZINE PLENUM SYSTEM

Inspection of this relationship shows that heat release, hence adiabatic temperature, is highest with no dissociation and decreases with increasing dissociation. This situation is shown in Figure 6.3-5. The molecular weight of exhaust gases and the chamber temperature also are shown to decrease with increasing ammonia dissociation.

The designer can control decomposition and dissociation to a certain extent by influencing flow variables and engine geometry. These factors are also affected by the type of catalyst and how it is used. The "spontaneous" nature of the Shell 405 catalyst (i.e., it needs no other means of ignition) makes it a leading candidate in hydrazine applications either by itself or in combination with other catalysts. Propellant decomposition is controlled by the exposure it has to the catalyst. Thus, important catalyst design parameters are area, catalyst bed length and ratio of propellant flow rate to catalyst bed cross-sectional area. Ammonia dissociation is also influenced by these factors, especially with the Shell 405 catalyst. A specific catalyst bed length is required for 100% hydrazine decomposition under given conditions. However, ammonia dissociation will also commence in the catalyst bed to the extent that there can be 30% or more dissociation by the time that 100% hydrazine decomposition has occurred. This means that reaction temperatures of 2200°F or less can be expected which is convenient in that it permits relatively simple radiation cooled engine designs with currently available materials.

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6.3.3 MONOPROPELLANT THRUSTOR CONSTRUCTION

The general design features of hydrogen peroxide or hydrazine monopropellant thrusters are quite similar. Downstream from the propellant flow control valve is an inlet and manifold for distributing propellant to the injector. Adjacent to the injector is a "catalyst bed" comprised of materials which sustain propellant decomposition by catalysis. It is desirable that the catalyst also initiate the catalytic process through other devices are sometimes necessary for ignition. These methods either raise catalyst bed temperature to a level which will promote decomposition or a brief hypergolic reaction is initiated. This is done with electric or isotope heaters or by introducing small amounts of oxidizer to react hypergolically with the propellant. The catalyst bed is retained by structural baffles through which exhaust passes into the convergent-divergent nozzle section.

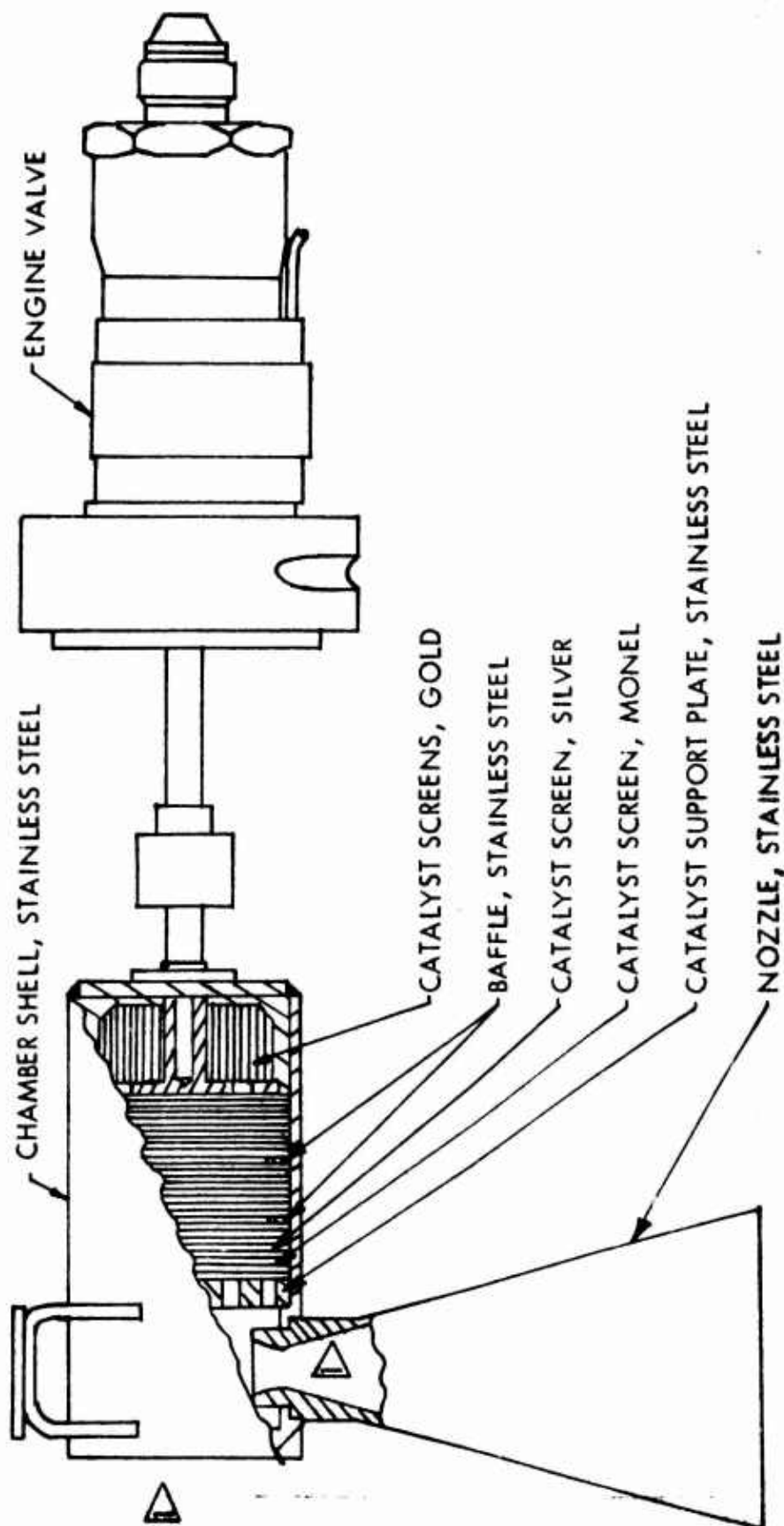
The specific design features of hydrogen peroxide and hydrazine monopropellant thrusters are sufficiently different to be discussed individually.

6.3.3.1 HYDROGEN PEROXIDE THRUSTOR CONSTRUCTION

A monopropellant hydrogen peroxide thruster consists of an injector, thrust chamber, catalyst bed with catalyst, nozzle and, commonly, the propellant valve. The thrust chamber with catalyst are frequently referred to as the reactor. The catalyst bed consists of a metal catalyst in screen form, stacked in such a manner as to promote even flow distribution across the catalyst area.

A typical hydrogen peroxide thruster is shown in Figure 6.3-6. This thruster uses a "staged" catalyst bed design in which different materials, construction or flow direction are involved in different phases of the decomposition process. Initially, propellant is admitted to the chamber by the propellant flow control valve, often referred to as the "engine valve." Propellant is distributed

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△ Thruster can be designed for nozzle installation at either location

FIGURE 6.3-6 TYPICAL HYDROGEN PEROXIDE THRUSTOR

(Ref. 23)

radially from a central injector into a gold catalyst screen to preheat the engine and propellant. The gas flow is then directed through the main catalyst bed composed primarily of silver catalyst screens. Final catalyst screens are made of muel. Anti-channel baffles are used to prevent bypassing the catalyst bed at start-up. Retainer screens are installed in such a way as to prevent local "hot spots" which can damage the catalyst bed. These screens are held in place by a baffled support plate.

Structural materials for the chamber walls, "head" and "tail" ends, support plate, and nozzle sections are generally of 321 or 347 stainless steel used with welded construction. The 304L or 316L stainless steels can also be used. The heavier thrustors use 347 stainless steel due to its superior strength at elevated temperatures.

6.3.3.2 HYDRAZINE THRUSTOR CONSTRUCTION

A monopropellant hydrazine thrustor consists of an injector, thrust chamber, catalyst bed with catalyst, and nozzle. The thrust chamber and catalyst bed are called the reactor. The catalyst bed consists of a catalyst in granular form which is held in place by various screens and supports.

A typical hydrazine thrustor is shown in Figure 6.3.7. This thrustor uses a "staged" ("layered") catalyst bed design in which different types and sizes of catalytic material are arranged in the bed in layers to support a particular phase of the decomposition process. Propellant is admitted to the chamber by the engine valve to and through the injector into the catalyst bed. Injector designs for hydrazine engines vary by manufacturer such that baffled plate or showerhead-type injectors (Figure 6.3-7) are used by some while others use perforated probe or coil units which penetrate into the catalyst bed.

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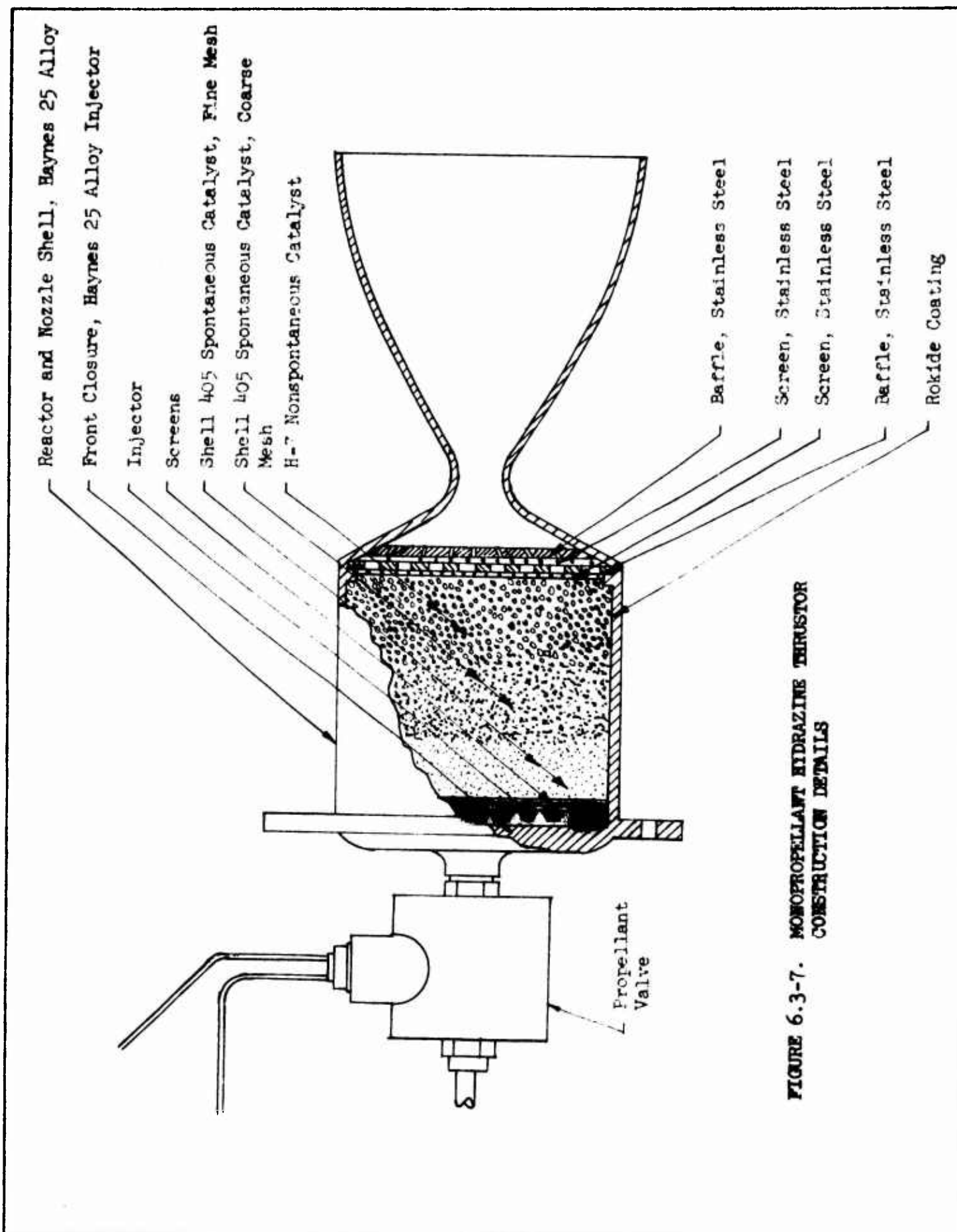


FIGURE 6.3-7. MONOPROPELLANT HYDRAZINE THRUSTOR
CONSTRUCTION DETAILS

This thruster design is based on the use of a "spontaneous" catalyst, such as Shell 405, which spontaneously initiates the decomposition process on contact, under ambient temperature conditions. Older catalysts, such as the H-7 used in Ranger and Mariner hydrazine engines used small quantities ("slugs") of nitrogen tetroxide (N_2O_4) reacting hypergolically for start-up. Other designs at that time involved electrical or isotopic heaters in the catalyst bed to raise bed temperature to a level at which it would initiate the decomposition process. The advent of spontaneous catalysts, especially the Shell 405 catalyst, has largely replaced these approaches.

The actual composition of the Shell 405 catalyst remains a classified item. Basically, it consists of a high surface area ceramic binder impregnated with metals which are catalytically very active. This arrangement is satisfactory for chamber temperatures of up to 1800°F, but the binder becomes structurally insufficient much beyond this point. Research has been, and is being, conducted to develop higher temperature binders for use with the higher performance hydrazine (N_2H_4)/hydrazinium nitrate ($N_2H_5NO_3$) mixtures which decompose at higher temperatures.

The Shell 405 catalyst originally cost about \$1500 per pound, and the price has not changed significantly. It is available on a standard basis in 1/8 by 1/8 inch or 1/8 by 1/16 inch cylindrical pellets. It is also marketed in fines crushed from basic pellets in 10-30 mm granules and microspheres from 0-5 to several millimeters in diameter. However, the 1/8 inch cylindrical pellet is still the standard form. The 1/8 by 1/8 inch pellet is the maximum pellet size currently available.

The catalyst is arranged by layers in the reactor such that the finest, highest surface area particles are adjacent to the injector to promote smooth ignition

and operation. These particles may be lightly fused in the first engine firing which promotes catalyst bed strength and lengthens catalyst life since very small particles can be easily dislodged from the engine. Sometimes the Shell 405 catalyst is used adjacent to the injector and backed up by the conventional H-7 catalyst to save cost and extend life. In this case, the Shell catalyst is used for the spontaneous ignition feature and the H-7 catalyst is used for extended life requirements.

Chamber construction is usually of thin-wall Haynes 25 alloy for the chamber walls, front and aft closures, and nozzle assembly. Sometimes, in small engines, these parts are made of 347 or similar stainless steels. Interior chamber walls are coated with Rokide or similar substances. Catalyst screens and support plates are made from 310 or similar stainless steels. Injectors are usually tubes or plates of aluminum alloys carefully selected and designed to survive the thermal conditions accompanying and following operation.

Engine design generally permits welding the aft closure-nozzle section to the chamber wall and inserting the catalyst support plate, catalyst, and upper screen. The forward closure, injector plates and/or tubes are installed in place, and this assembly mated with the upper chamber wall and welded at this point. A design preference has involved placing the engine mounting lugs at the forward closure weld for a thermal relief path after engine operation. However, the mounting ring has also been located upstream of the injector head in the vicinity of the engine valve. Location of the engine valve and inlet manifold is sometimes extended farther upstream of the catalyst face for thermal standoff.

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6.3.4 MONOPROPELLANTS

Numerous compounds, or mixtures of compounds, have been suggested for use as monopropellants. However, many have been discarded in view of the stability and handling requirements of the operational situation. The most frequently mentioned monopropellants include hydrogen peroxide, hydrazine, hydrazine-hydrazinium nitrate, ethylene oxide, nitromethane and tetranitromethane. Of these, hydrogen peroxide and hydrazine are the only monopropellants to receive extensive use. The characteristics of these monopropellants, and their variations, will be separately discussed in the following sections.

6.3.4.1 HYDROGEN PEROXIDE (H_2O_2)

Hydrogen peroxide has been used to drive turbines in both rocket engines and AFU's and as a monopropellant in attitude and velocity control systems. Its performance is directly related to the percent of peroxide in the peroxide-water solution. Currently, 90% peroxide is used most frequently though increasing emphasis is being placed on 98%. Characteristics of both varieties are shown in Table 6.3-1. Peroxide solutions are insensitive to the initiation and propagation of detonations. Although the decomposition products are oxidizing, the flame temperature is low enough to preclude significant materials problems. Decomposition is usually initiated by a suitable catalyst such as permanganate salts, or activated silver screens. Storage and handling of peroxide is complicated by the fact that it reacts to some extent with almost every substance. Peroxide systems must be kept quite clean to prevent accidental catalysis. Thus it is necessary to clean and chemically treat materials that will be exposed to the liquid. Even so, there will be a slight concentration loss (0.5-1.0% per year) during long storage periods. Absolute viscosity, density and vapor pressure of 90% hydrogen peroxide are shown in Figure 6.3-8 as a function of temperature. Density is shown in Figure 6.3-9 as a function of peroxide concentration.

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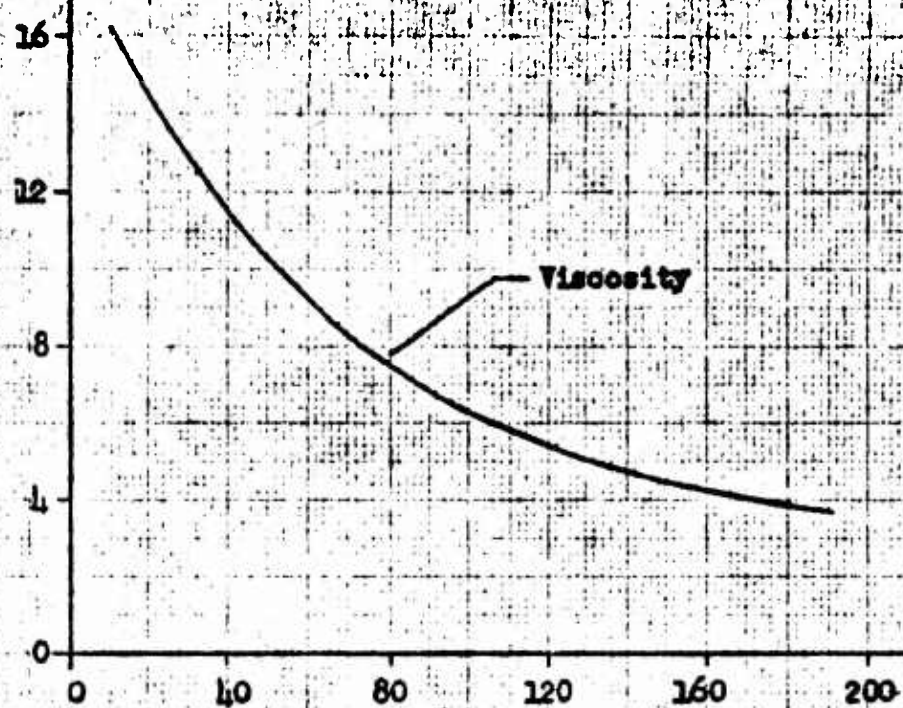
TABLE 6.3-1
PROPERTIES OF HYDROGEN PEROXIDE

| | | <u>CONCENTRATION BY WEIGHT</u> | | |
|--|------------------------------------|--------------------------------|------------------------|-------------|
| | | <u>90%</u> | <u>98%</u> | <u>100%</u> |
| Average Molecular Weight | | 31.241 | 33.422 | |
| Normal Boiling Point | °R | 746.2 | 759.2 | |
| Normal Freezing Point | °R | 471.3 | 487.5 | |
| Density (@ 537°R) | g/cc | 1.383 | 1.431 | |
| Vapor Pressure (@ 537°R) | PSI | .0735 | .0426 | |
| Critical Pressure | PSI | | | 3144.98 |
| Critical Temperature | °R | | | 1318 |
| Dielectric Constant | | 77 | 77 | |
| Electrical Conductivity (@ 537°R) | ohm ⁻¹ cm ⁻¹ | 1,9(10 ⁻⁶) | 0.8(10 ⁻⁶) | |
| Fire Point | | | | |
| Flash Point | | | | |
| Heat Capacity, Liquid (492-533°R) | Btu/lb°F | | | 58.0 |
| Heat of Decomposition (@ 537°R) | Btu/lb SOLID | 1108 | 1215 | |
| Heat of Formation, Liquid (@ 537°R) | Btu/lb | | | 2369 |
| Heat of Fusion | Btu/lb SOLID | | | 158.1 |
| Heat of Dilution to Infinite (@ 537°R) | " | -31.2 | -41.0 | |
| Heat of Vaporization, Total, SOLID | Btu/lb | 700.3 | 662.0 | |
| Viscosity (@537°R) | Centipoise | 1.153 | 1.155 | |

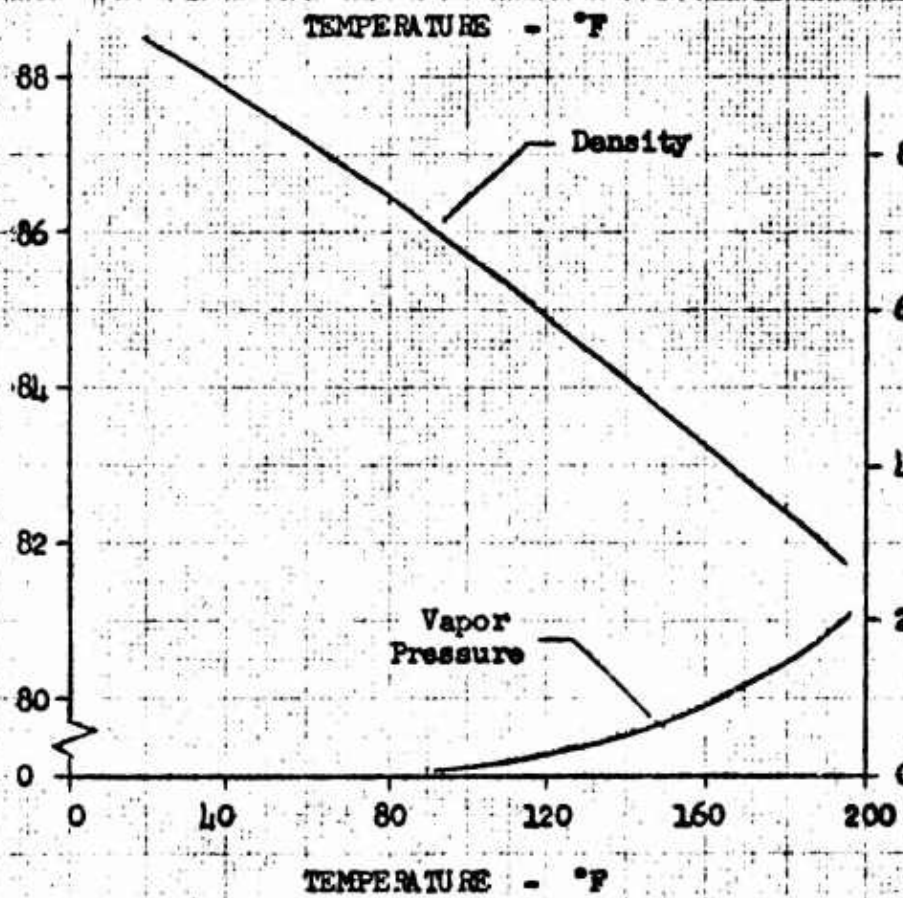
(Refs. 22 and 24)

DS-11111-2

ABSOLUTE VISCOSITY - 10^{-4} lbs/ft-sec

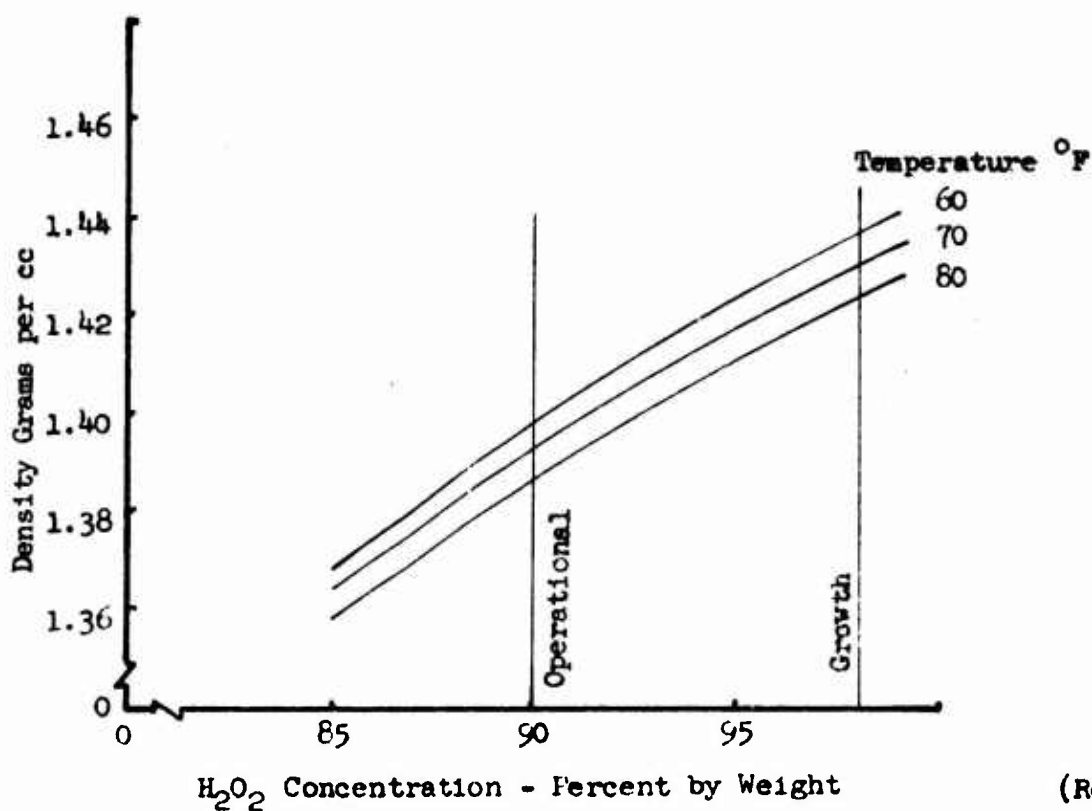


DENSITY - lbs/ft³



(Ref. 4)

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|------|--|---------|---------|------|-------|--|--|--|--|-----|--|--|--|--|-----|--|--|--|--|--|--|-----------------------------------|
| <table border="1"> <tr> <td>CALC</td> <td></td> <td></td> <td>REVISED</td> <td>DATE</td> </tr> <tr> <td>CHECK</td> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td>APR</td> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td>APR</td> <td></td> <td></td> <td></td> <td></td> </tr> </table> | CALC | | | REVISED | DATE | CHECK | | | | | APR | | | | | APR | | | | | <p>PHYSICAL PROPERTIES 90% HYDROGEN PEROXIDE</p> <p>THE BOEING COMPANY</p> | | <p>FORM 6.3-81</p> <p>PAGE 94</p> |
| CALC | | | REVISED | DATE | | | | | | | | | | | | | | | | | | | |
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| APR | | | | | | | | | | | | | | | | | | | | | | | |



(Ref. 25)

FIGURE 6.3-9 DENSITY OF HYDROGEN PEROXIDE

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6.3.4.2 HYDRAZINE (N_2H_4)

Hydrazine has been used as a turbine-drive gas, as well as a monopropellant in attitude and velocity control systems. It is a clear, colorless, hygroscopic, toxic, flammable, caustic liquid and a strong reducing agent. "Neat" or anhydrous hydrazine used in rocket engines is controlled by MIL Spec MIL-P-28536B. Physical properties of hydrazine are listed in Table 6.3-2. Density, specific heat, vapor pressure and viscosity of hydrazine are shown in Figure 6.3-10 as a function of temperature.

Hydrazine is compatible with most stainless steels, aluminum, tantalum, titanium, Haynes 25 alloy, teflon, polyethylene, glass, butyl rubber, and ethylene propylene.

Considerable research effort has been expended on reducing the relatively high freezing point of hydrazine (35.6°F) by adding water, ammonia, or hydrazine nitrate. Simple binary or tertiary solutions of these compounds form low freezing point eutectics. These mixes also change other characteristics of the propellants, including density and performance. Figure 6.3-11 shows how hydrazine freezing point changes with water addition. The density variation of solutions of hydrazine, hydrazine nitrate, and water are shown in Figure 6.3-12 as a function of temperature. The physical properties of hydrazine-ammonia solutions are shown in Figure 6.3-13 as a function of ammonia content.

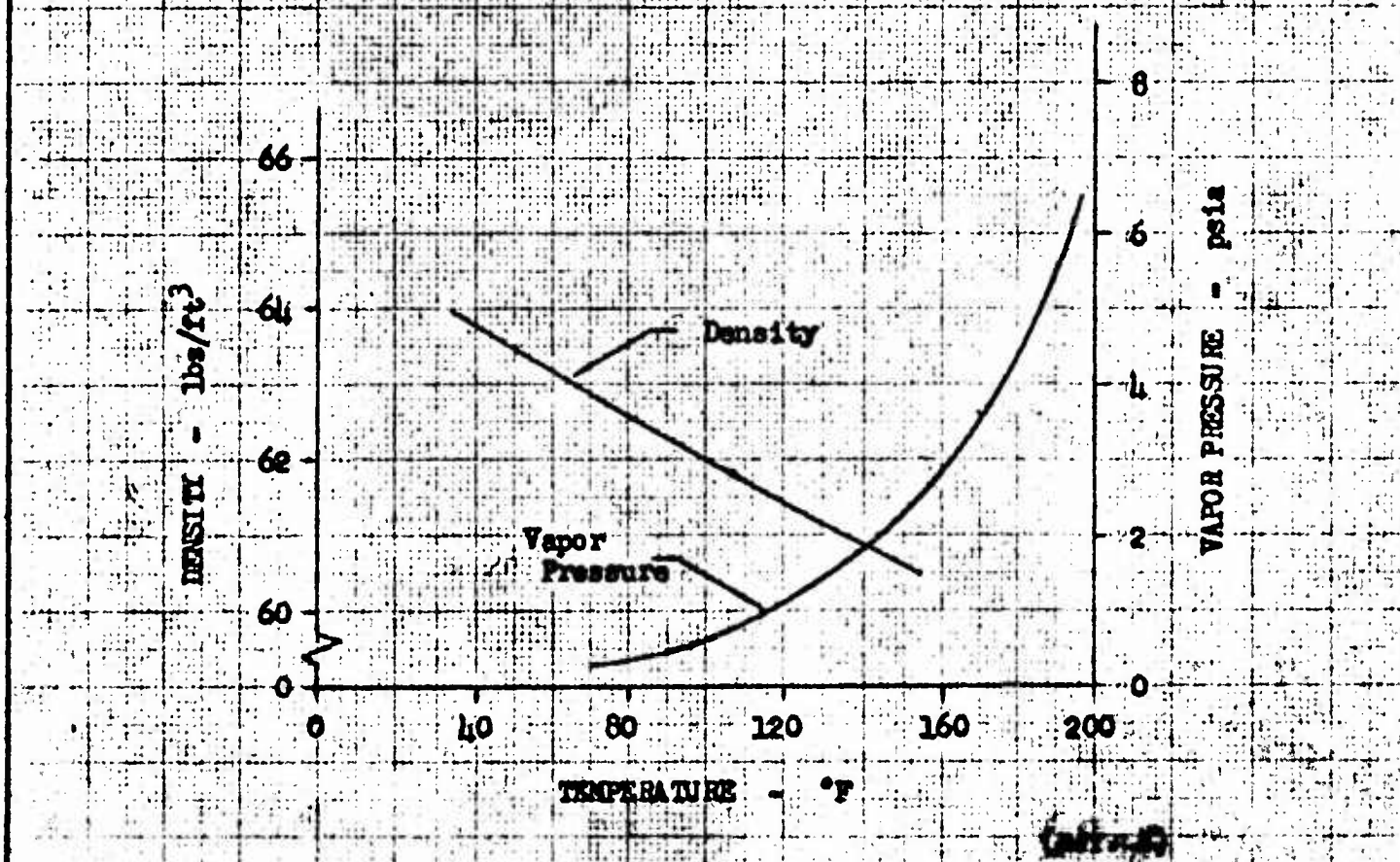
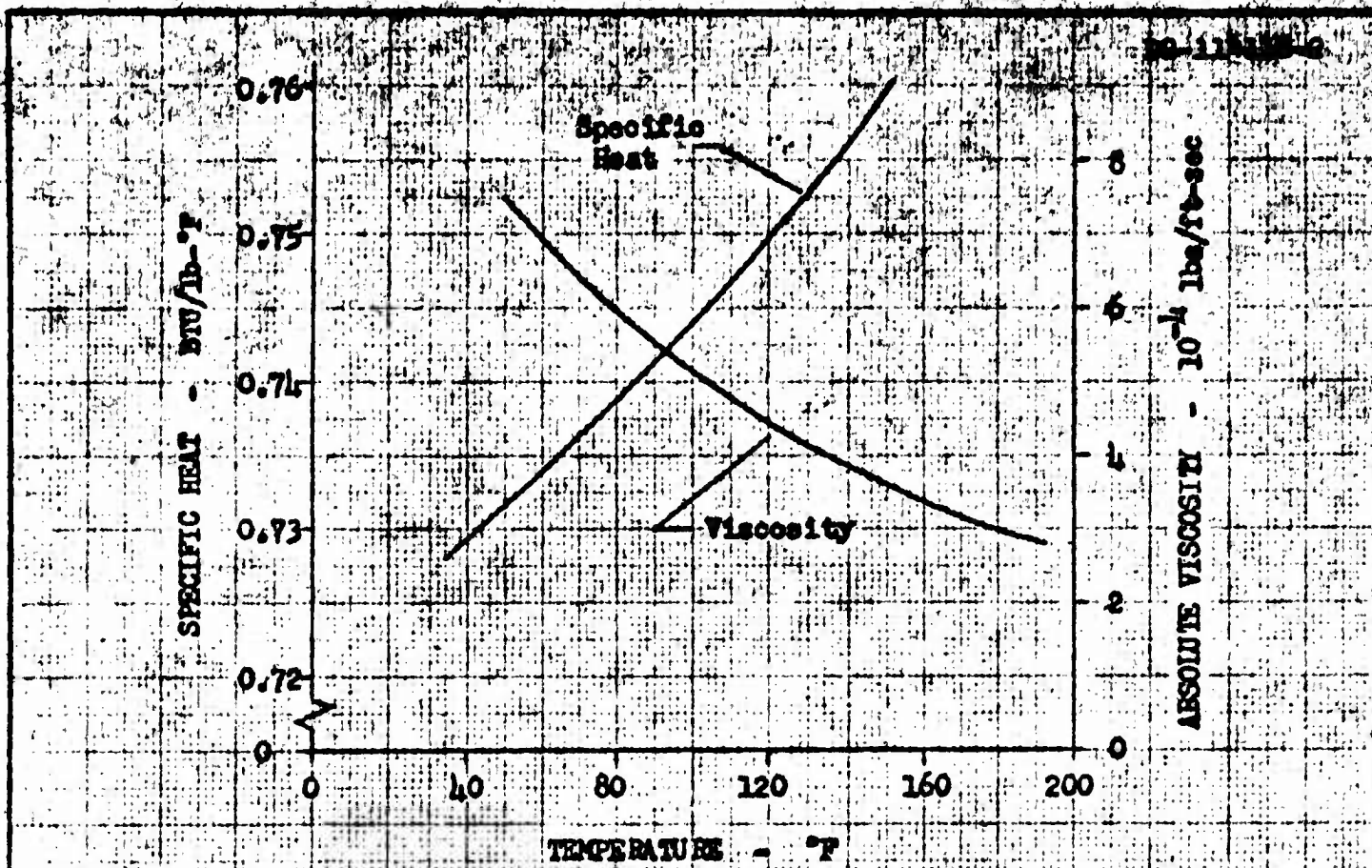
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TABLE 6.3-2
PROPERTIES OF HYDRAZINE

| | |
|--|--|
| Molecular Formula | N_2H_4 |
| Molecular Weight | 32.05 |
| Normal Boiling Point | 696.3°R |
| Normal Freezing Point | 495.6°R |
| Density (@ 528°R) | 1.0083 g/cc |
| Vapor Pressure (@ 537°R) | 0.28 psia |
| Critical Pressure | 2132 psia |
| Critical Temperature | 1176°R |
| Dielectric Constant (@ 537°R) | 51.7 |
| Electrical Conductivity (@ 537°R) | 2.3-2.8(10^{-6}) ohm ⁻¹ |
| Fire Point (Tag Open Cup) | 585.6°R |
| Flash Point (Tag Open Cup) | 585.6°R |
| Heat Capacity (liquid) (@ 537°R) | 0.737 Btu/lb°R |
| Heat of Combustion (to $N_2 + 2H_2O$ liq)(@ 537°R) | -8,359 Btu/lb |
| Heat of Formation, Liquid (@ 537°R) | 676 Btu/lb |
| Heat of Fusion (@ 495.6°R) | 170 Btu/lb |
| Heat of Solution, Liquid (@ 537°R) | -219.6 Btu/lb |
| Heat of Vaporization (@ 696.3°R) | 540 Btu/lb |
| Viscosity (@ 537°R) | 0.90 centipoises |

(Refs. 24 and 26)

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| | | | | | | |
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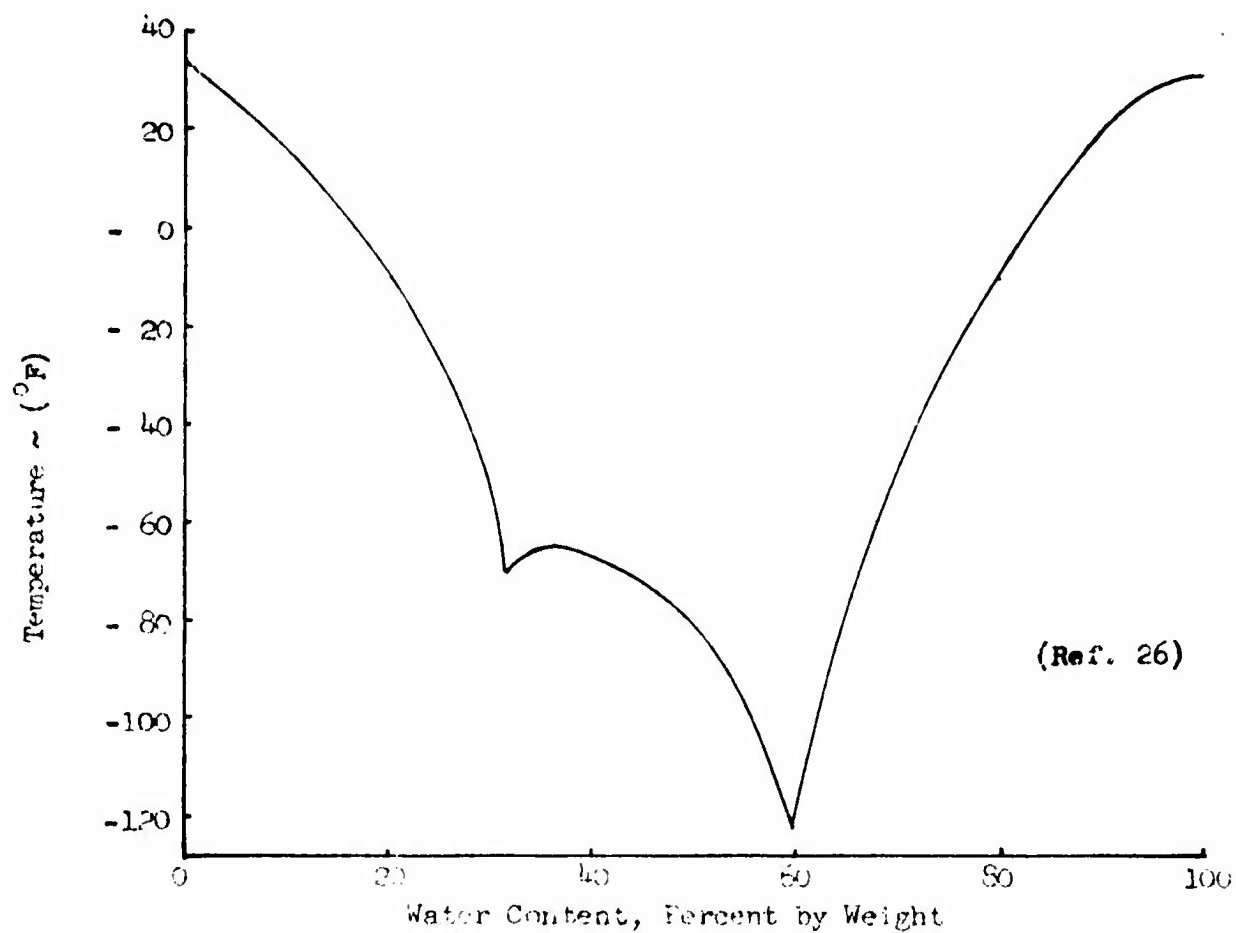


FIGURE 6.3-11 FREEZING POINT OF HYDRAZINE AND WATER SOLUTIONS

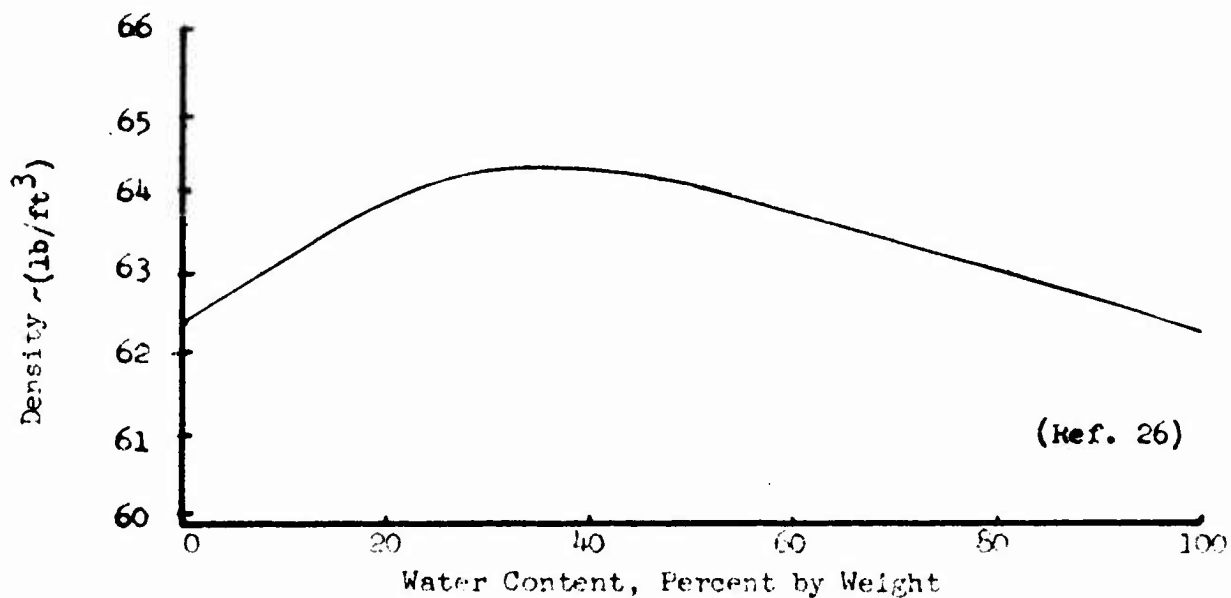


FIGURE 6.3-12 SPECIFIC GRAVITY OF HYDRAZINE AND WATER SOLUTIONS

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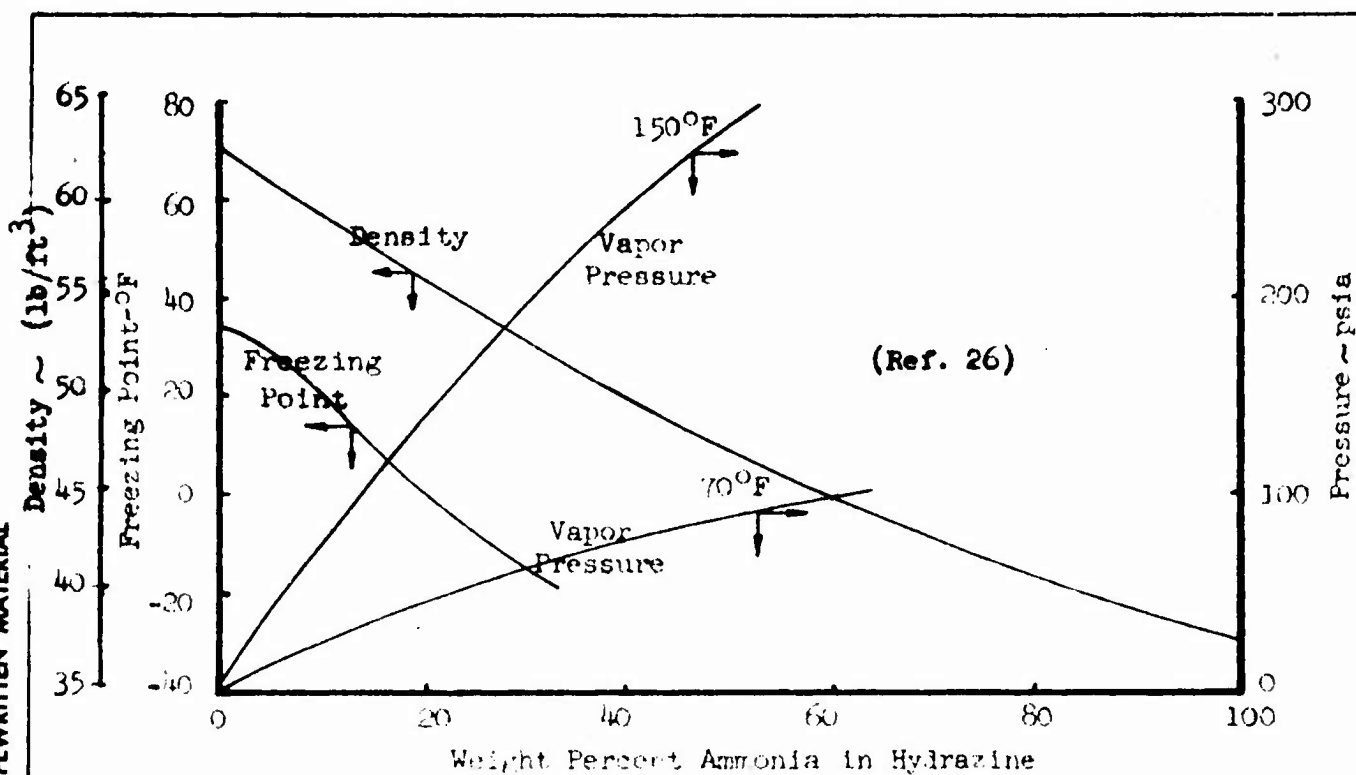


FIGURE 6.3-13 PHYSICAL PROPERTIES OF HYDRAZINE AND AMMONIA SOLUTIONS

6.3.5 MONOPROPELLANT PERFORMANCE

The performance of hydrogen peroxide and of hydrazine are compared in a general fashion in Figure 6.3-14 as a function of duty cycle and pulse width. The superior performance of hydrazine is apparent, especially as operation approaches steady state conditions. More detailed performance information for these propellants is provided in the following sections.

6.3.5.1 PERFORMANCE - HYDROGEN PEROXIDE

Hydrogen peroxide decomposes exothermally to superheated oxygen gas and water vapor. Figure 6.3-3 shows the decomposition gas temperature of hydrogen peroxide, in various concentrations, as a function of chamber or reactor pressure.

The theoretical specific impulse of hydrogen peroxide is shown in Figure 6.3-15 as a function of peroxide concentration. Propellant gamma is related to peroxide concentration in Figure 6.3-16. The performance improvement possible with 98% peroxide, including the increased specific impulse, and increased propellant density for equal volume applications, is approximately 13%.

Delivered specific impulse under steady state conditions with 90% hydrogen peroxide is shown in Figure 6.3-17 as a function of nozzle expansion ratio. In pulsing operation, performance can be expected to follow that shown in Figure 6.3-18 in which delivered specific impulse is related to pulse length and the spacing between pulses. Figure 6.3-19 shows how several different engines using 90% hydrogen peroxide perform in pulsed operation.

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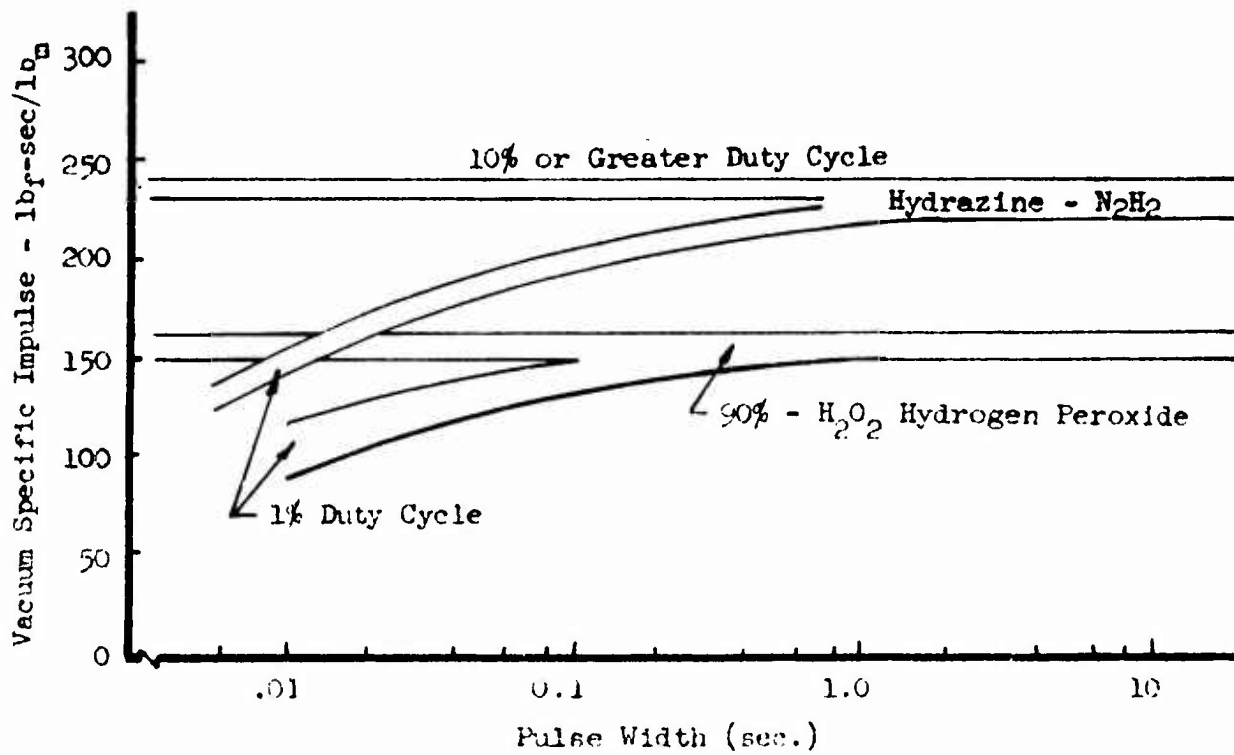


FIGURE 6.3-14.

PERFORMANCE OF COMMON MONOPROPELLANTS

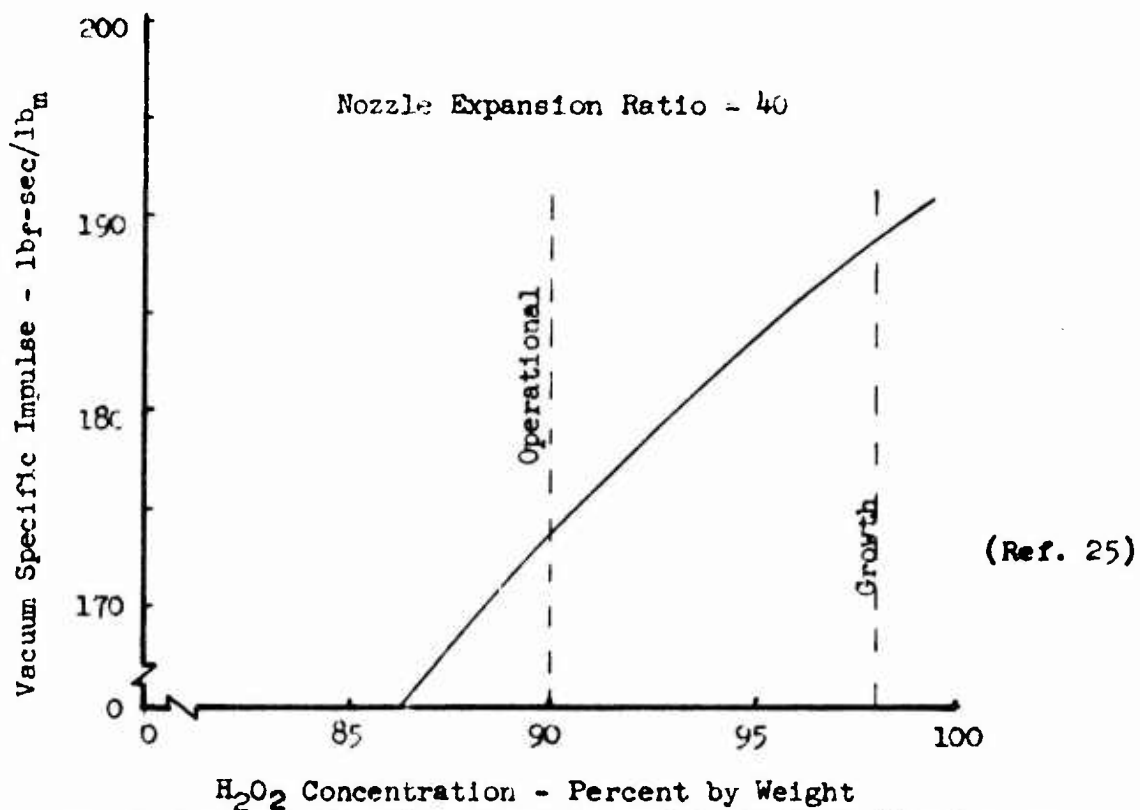


FIGURE 6.3-15. THEORETICAL PERFORMANCE OF HYDROGEN PEROXIDE

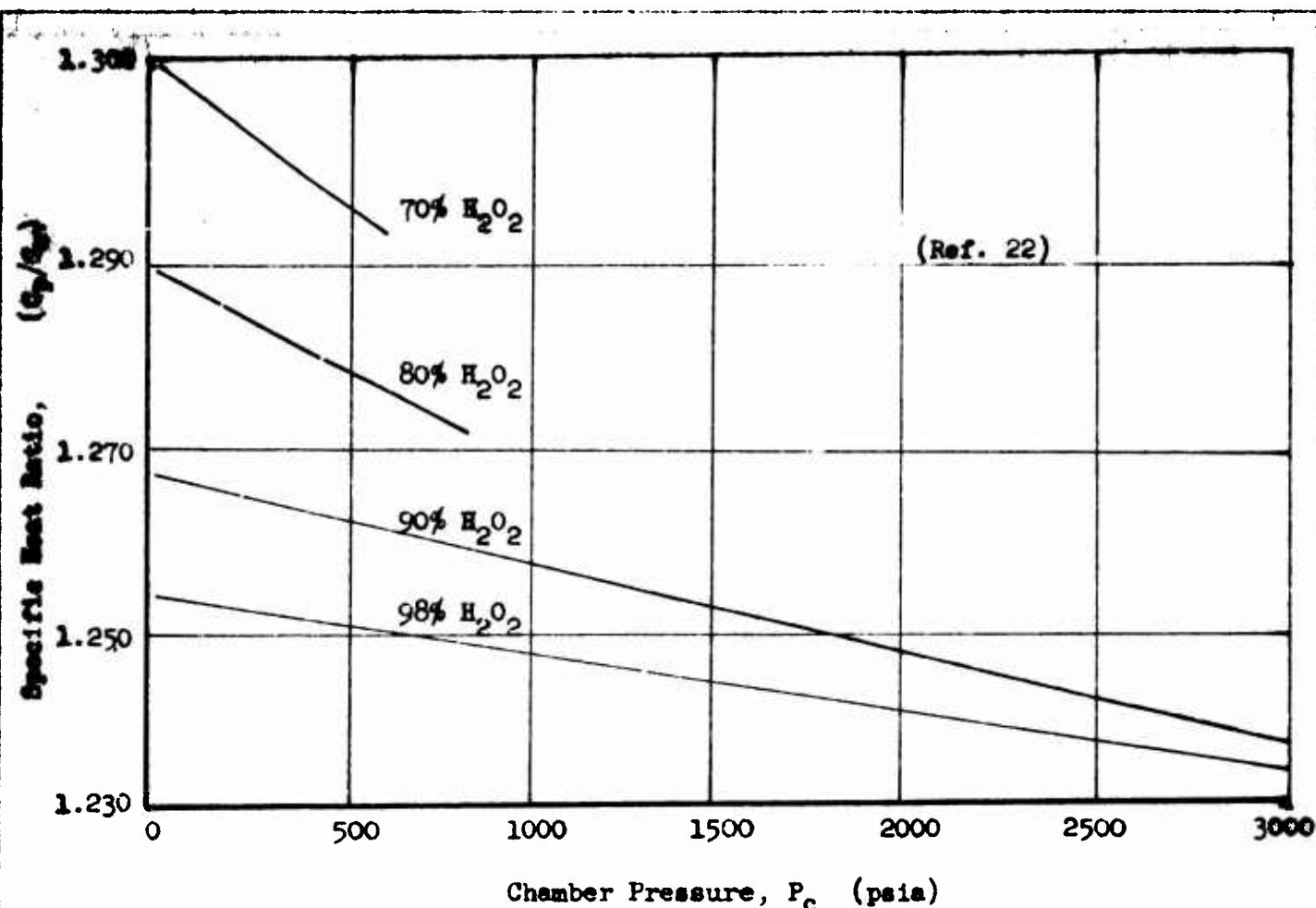


Figure 6.3-16 SPECIFIC HEAT RATIO OF HYDROGEN PEROXIDE

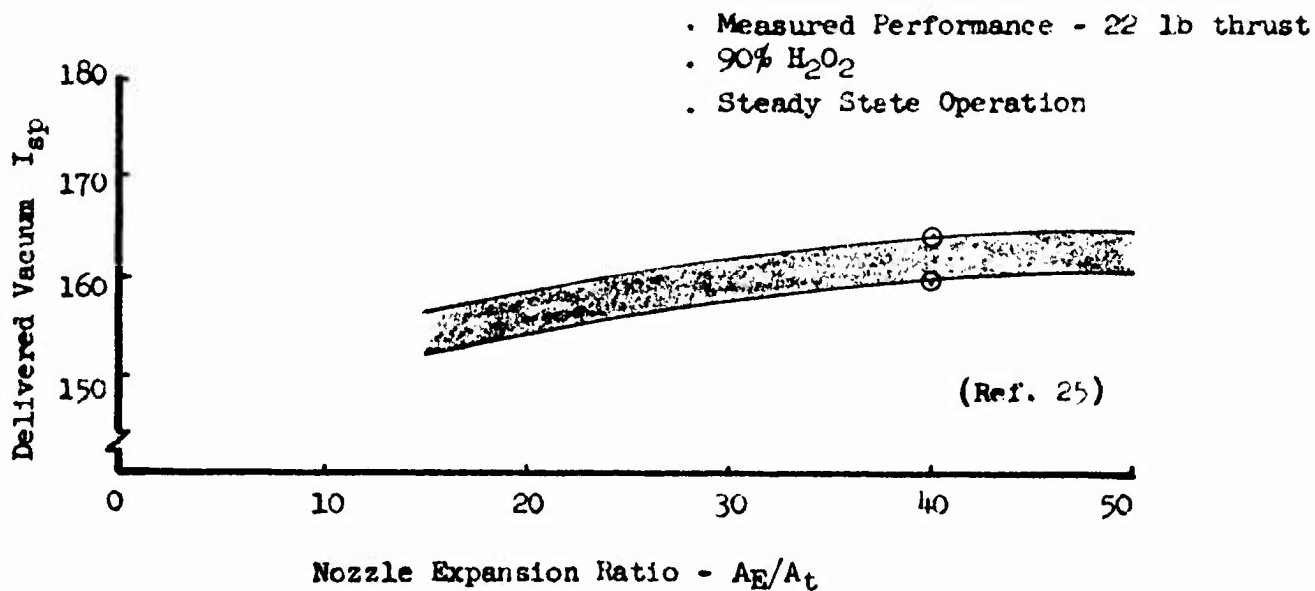


FIGURE 6.3-17 HYDROGEN PEROXIDE DELIVERED PERFORMANCE

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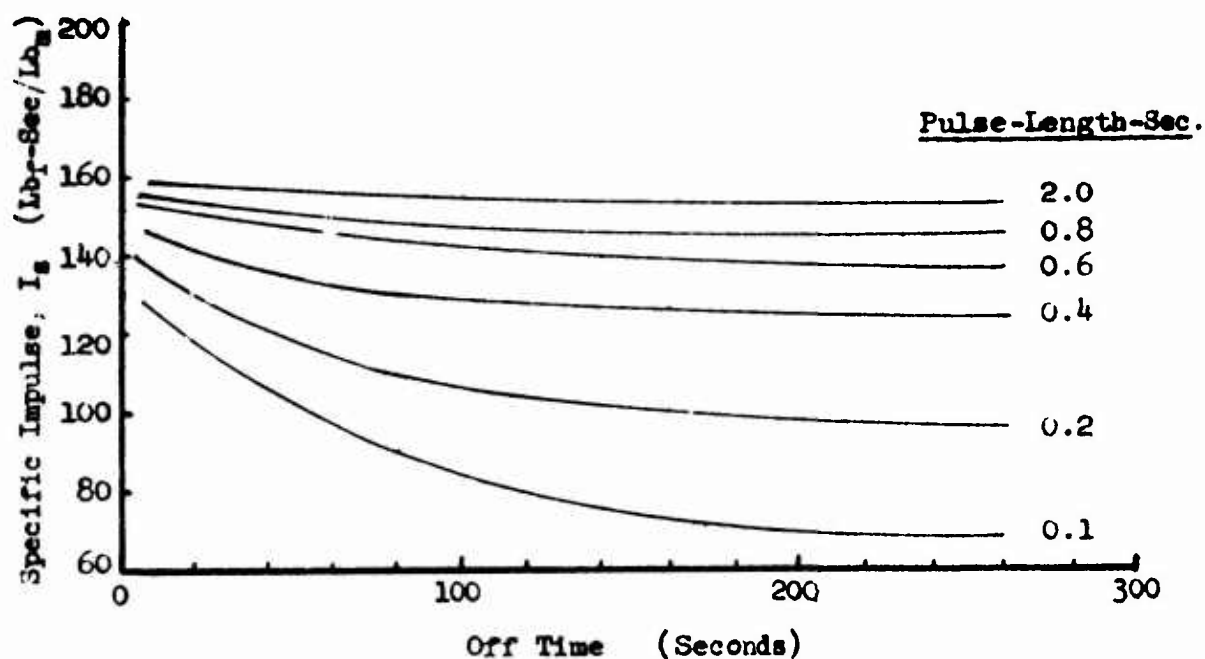


FIGURE 6.3-18 90 PERCENT HYDROGEN PEROXIDE PERFORMANCE
IN PULSED OPERATION (Ref. 4)

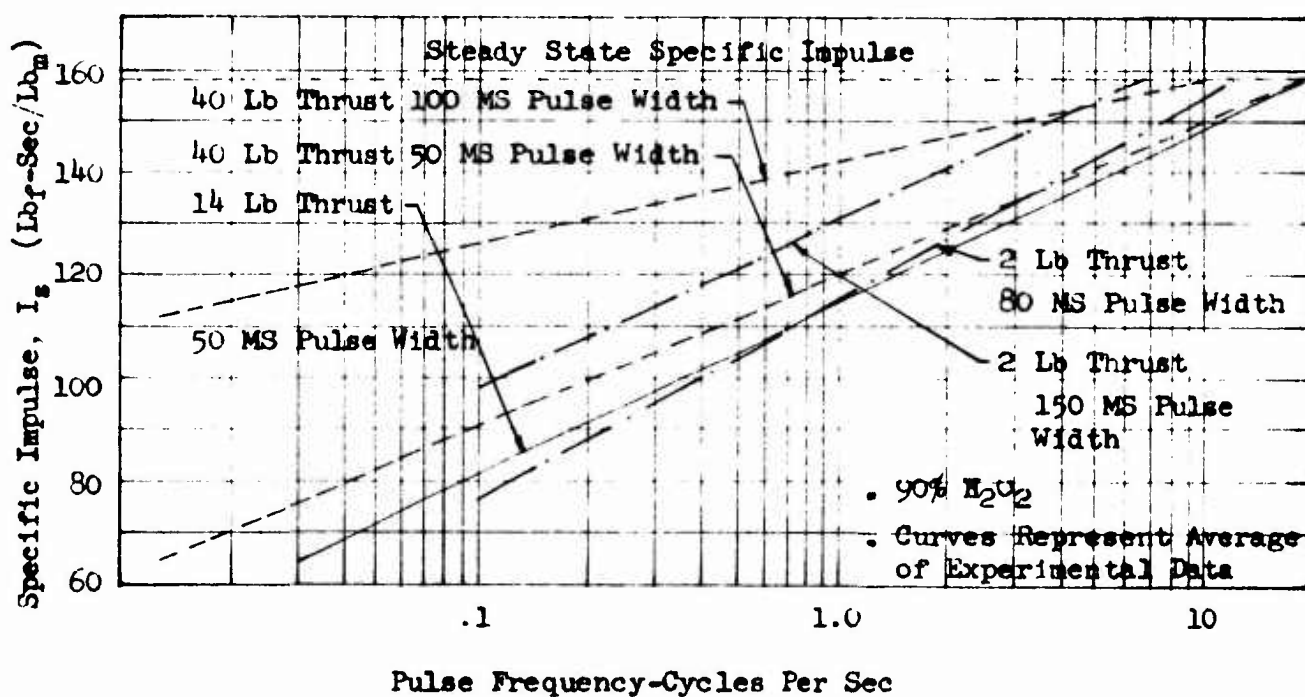


FIGURE 6.3-19 HYDROGEN PEROXIDE PERFORMANCE IN
PULSED OPERATION - DEMONSTRATED (Ref. 2)

6.3.5.2 PERFORMANCE - HYDRAZINE

Hydrazine decomposes exothermally to nitrogen gas and ammonia which partially dissociates to nitrogen and hydrogen. This decomposition reaction and dissociation process are related in expression 6.3-1 to the parameter, X , representing the fraction of ammonia dissociation. Figure 6.3-20 shows the performance of 100% hydrazine (N_2H_4) in terms of specific impulse, characteristic velocity (C^*), chamber temperature, and exhaust product mole weight and composition.

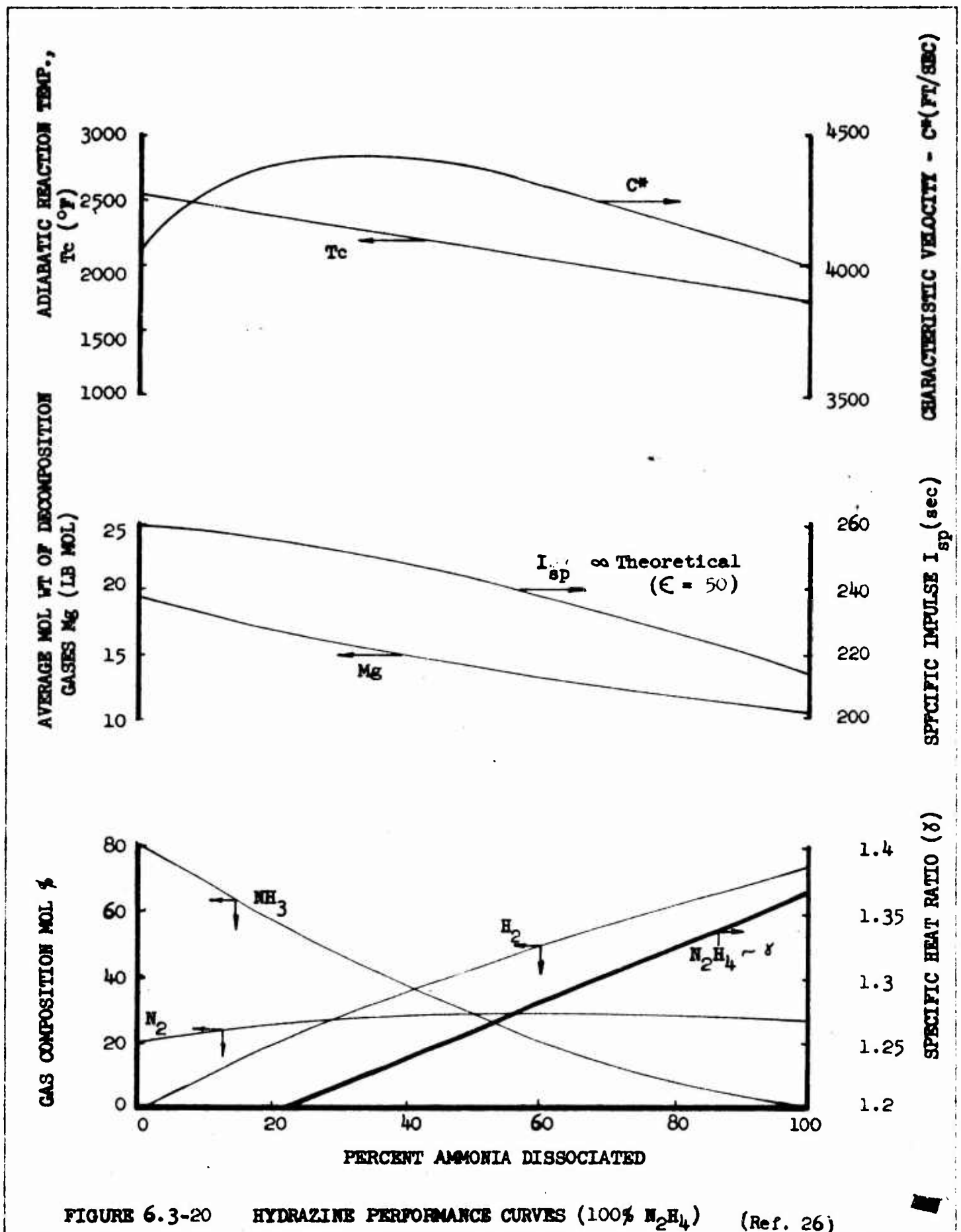
The performance actually delivered by monopropellant engines is affected primarily by nozzle expansion ratio, engine thrust level, and whether the engine was designed for steady-state or pulsing operation. Figure 6.3-21 shows delivered specific impulse as a function of thrust level for many different hydrazine engine designs. In preliminary design exercises, delivered specific impulse (vacuum, steady state) is generally assumed as 230-235 lbf-sec/lbm with engines larger than one pound thrust. Performance of very small engines may be assumed as low as 210 to 215 lbf-sec/lbm. These values are based on "hot bed" results. Cold bed performance is substantially lower, extending possibly to the cold bed temperature limit of approximately 118 lbf-sec/lbm for a 60°F "cold" catalyst bed.

Performance of a typical hydrazine engine under pulsed operation is shown in Figure 6.3-22 as a function of pulse width and the spacing between pulses.

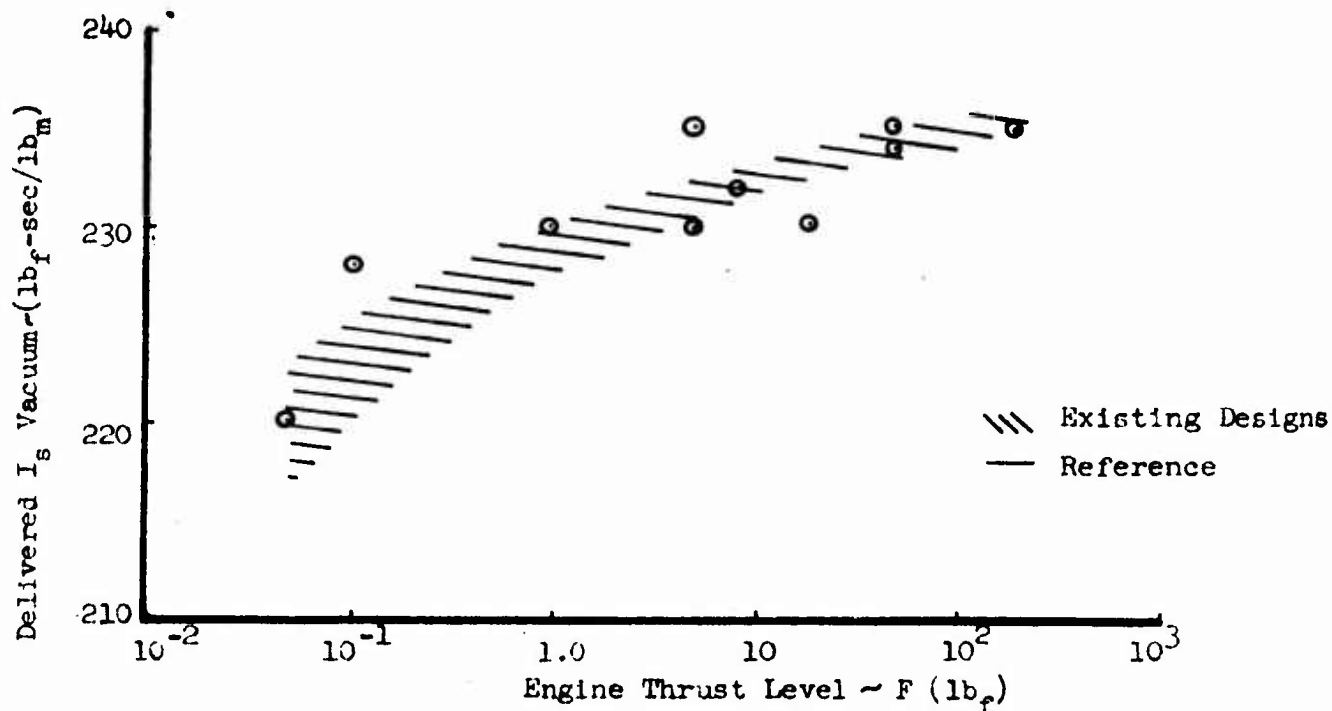
Minimum impulse bit capability of hydrazine engines is strongly affected by the engine-valve relationship, and by reactor design "learning curve" effects.

Minimum reproducible impulse bits (lb-sec) equal to 0.005 times the nominal thrust rating have recently been demonstrated in hydrazine engines from 2 to 50 lbs of thrust. Minimum reproducible impulse bit values ($I_{T_{min}}$) are shown in Figure 6.3-23 for existing hydrazine engine designs.

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6.3-21 STEADY STATE PERFORMANCE DELIVERED BY HYDRAZINE MONOPROPELLANT ENGINES

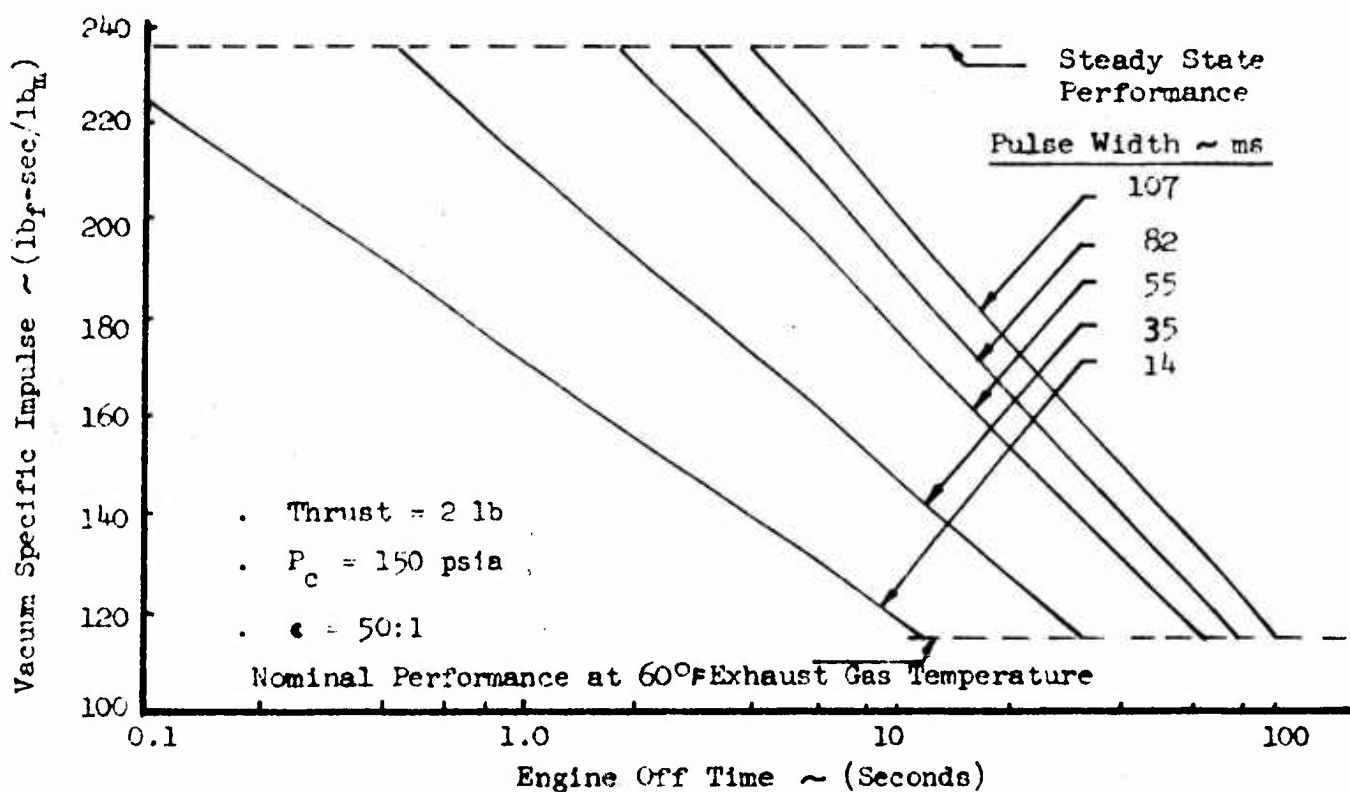


FIGURE 6.3-22 HYDRAZINE MONOPROPELLANT ENGINE PULSE PERFORMANCE CAPABILITY (Ref. 26)

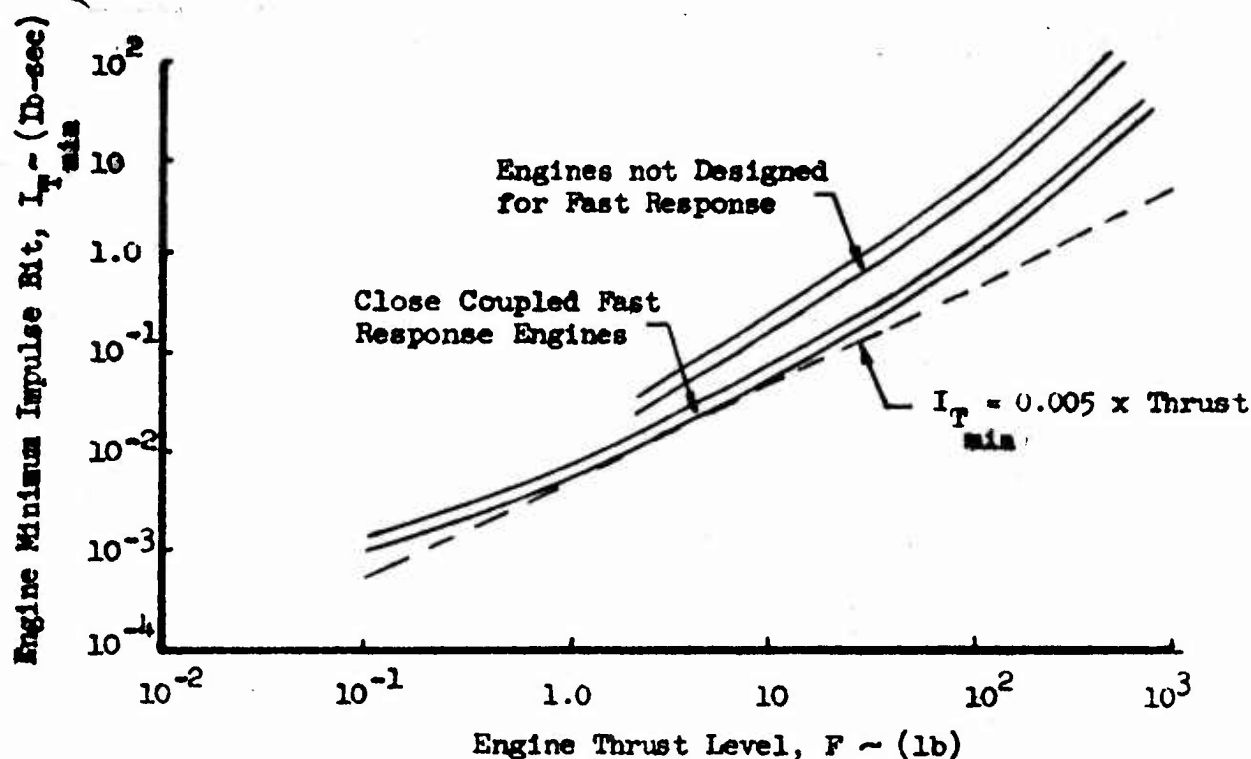


FIGURE 6.3-23 MINIMUM IMPULSE BIT CAPABILITY OF HYDRAZINE ENGINES

Caution should be exercised in selecting design values of $I_{T_{min}}$, since fast response systems can be substantially more expensive. This greater expense is due to more involved development programs, and selective engine delivery. Values of $I_{T_{min}}$ may be increased considerably where multiple engine valves are used for reliability purposes.

Impulse tolerance is usually specified in conjunction with minimum impulse requirements. These operations are always time related, and are thus sensitive to timing errors. As a general rule, engine minimum impulse tolerances may be estimated as $\pm 10\%$ of the minimum impulse bit, and are commonly stated that way. Some improvement is possible though, when necessary. Mariner II (Mariner R) which was accelerometer controlled was capable of $\pm 5\%$ tolerance on the minimum impulse bit. Where possible, it is suggested that impulse tolerance values shown in Figure 6.3-24 be used for design purposes.

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Hydrazine performance can be significantly improved by mixing it with hydrazinium nitrate ($\text{N}_2\text{H}_5\text{NO}_3$). Unfortunately, reaction temperatures of the mixture (2500°F) exceed the capability of the spontaneous catalyst binder, although they are within the capability of H-7 catalyst. Hydrazinium nitrate is also quite shock sensitive. Performance, decomposition temperature, shock sensitivity and propellant freezing point can be improved, however, by mixing the hydrazine and hydrazinium nitrate with water. Figure 6.3-25 is a ternary diagram of the mixture showing freezing point, specific impulse, and shock sensitivity as a function of the amount of each substance involved. Fair stability has been found with mixtures containing up to 15% hydrazinium nitrate, but shock sensitivity increases rapidly beyond this point.

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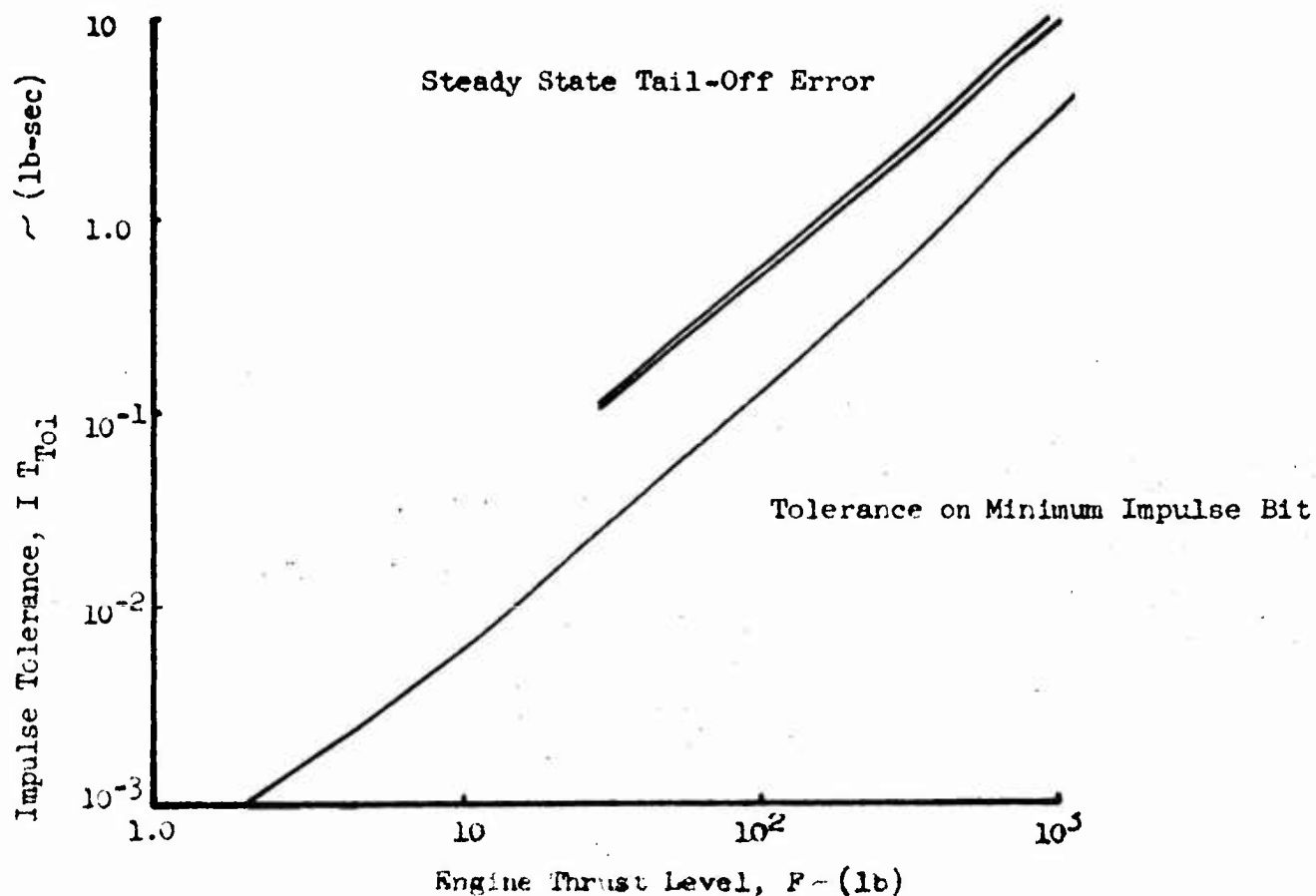
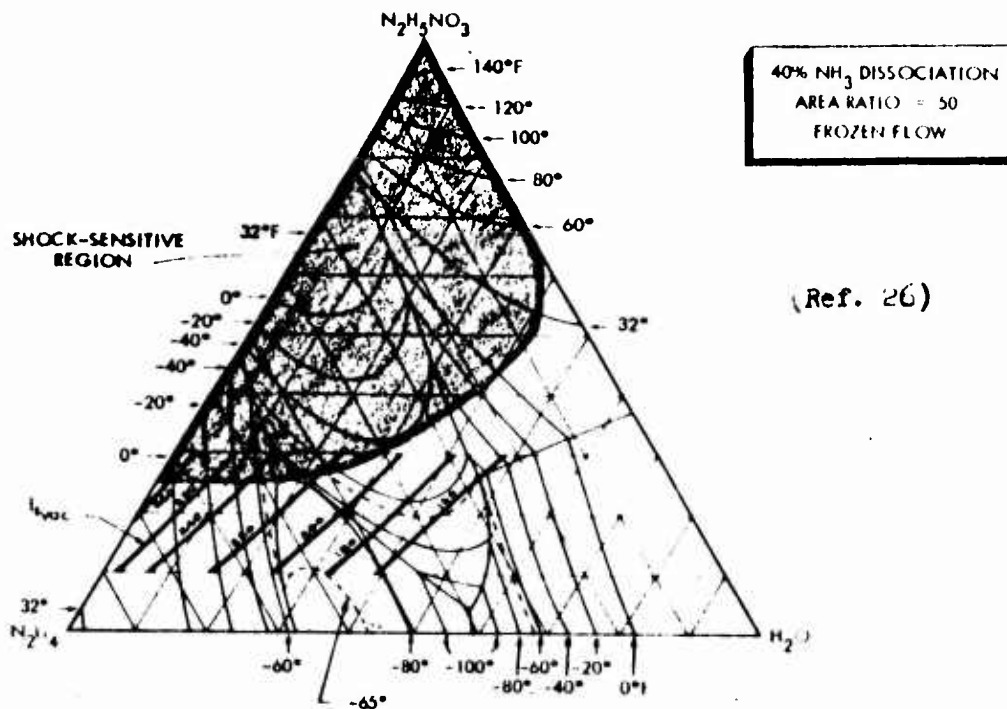


FIGURE 6.3-24 IMPULSE TOLERANCE FOR HYDRAZINE ENGINES



(Ref. 26)

FIGURE 6.3-25 HYDRAZINE-HYDRAZINE NITRATE - WATER
TERNARY DIAGRAM SHOWING FREEZING
POINT AND VACUUM SPECIFIC IMPULSE

6.3.6 MONOPROPELLANT THRUSTOR DESIGN

The design of monopropellant thrusters using hydrogen peroxide and those using hydrazine is sufficiently different to merit separate discussion. Their design is strongly affected by the particular catalyst used, which is quite different in the two systems. Variations in design, to accommodate more advanced propellants, such as 98% hydrogen peroxide, or the hydrazine-hydrazinium nitrate mixtures, can be treated on a preliminary basis as a simple change to basic design parameters. However, these changes actually involve significant materials changes due to the higher temperatures involved, hence should not be treated as currently operational approaches.

6.3.6.1 THRUSTOR DESIGN - HYDROGEN PEROXIDE ENGINES

Hydrogen peroxide thrusters can be configured, for preliminary design exercises, by using the procedure outlined below. Primarily, this concerns setting performance levels, defining catalyst configuration, and sizing the engine as shown in 6.3.8.1.

- 1) Assume engine thrust level, F , and duty cycle
- 2) Assume chamber pressure, P_c , and nozzle expansion ratio (ϵ)
- 3) Determine specific heat ratio, γ , for the propellant using Figure 6.3-16
- 4) Determine thrust coefficient, C_F , for the engine using Figures 5.1-1 and 5.2-5.
- 5) Estimate propellant specific impulse, I_s , by means of Figures 6.3-17 and 6.3-18 considering duty cycle effects
- 6) Determine propellant flow rate, \dot{w} , by

$$\dot{w} = \frac{F}{I_s} \quad (6.3-2)$$

- 7) Determine catalyst frontal area, A_c , by

$$A_c = K_c \dot{w} \quad (6.3-3)$$

where:

K_c = a constant relating catalyst frontal area to propellant flow rate. Peroxide thrusters with pre-heat sections use a K_c value of 4 in²/(lb/sec). If no pre-heat section is used, assume $K_c = 3$.

- 8) Assume catalyst pack length, L_b ;

$$L_b = 2.0 \text{ inches} \quad (6.3-4)$$

- 9) Define catalyst pack pressure drop, ΔP_{c_p} , by use of Figure 6.3-26.

- 10) Modify thruster design, or catalyst pressure drop when changing engine operating conditions, such as when operating at different pressure levels or when throttling, by:

$$(\Delta P_{c_p})_2 = (\Delta P_{c_p})_1 \left[\frac{K_{c1}}{K_{c2}} \right]^{1.9} \left[\frac{1.84 \log_e (L_{c2}) + 49.6}{1.84 \log_e (L_{c1}) + 49.6} \right] \left[\frac{P_{c1}}{P_{c2}} \right]^{0.92} \quad (6.3-5)$$

6.3.6.2 THRUSTOR DESIGN-HYDRAZINE THRUSTORS

Monopropellant hydrazine decomposes at relatively low temperatures. Figure 6.3-5 relates hydrazine decomposition temperature and molecular weight to the amount of ammonia dissociation involved. It is generally desirable to minimize ammonia dissociation to maximize performance within the temperature limitations of practical materials. However, minimum residence time requirements for complete hydrazine decomposition also result in approximately 30 percent ammonia dissociation. The decomposition temperature of hydrazine under these conditions allows the use of such materials as Haynes 25 alloy in conjunction with radiation cooled or radiation/heat sink engine designs, and the Shell 405 catalyst.

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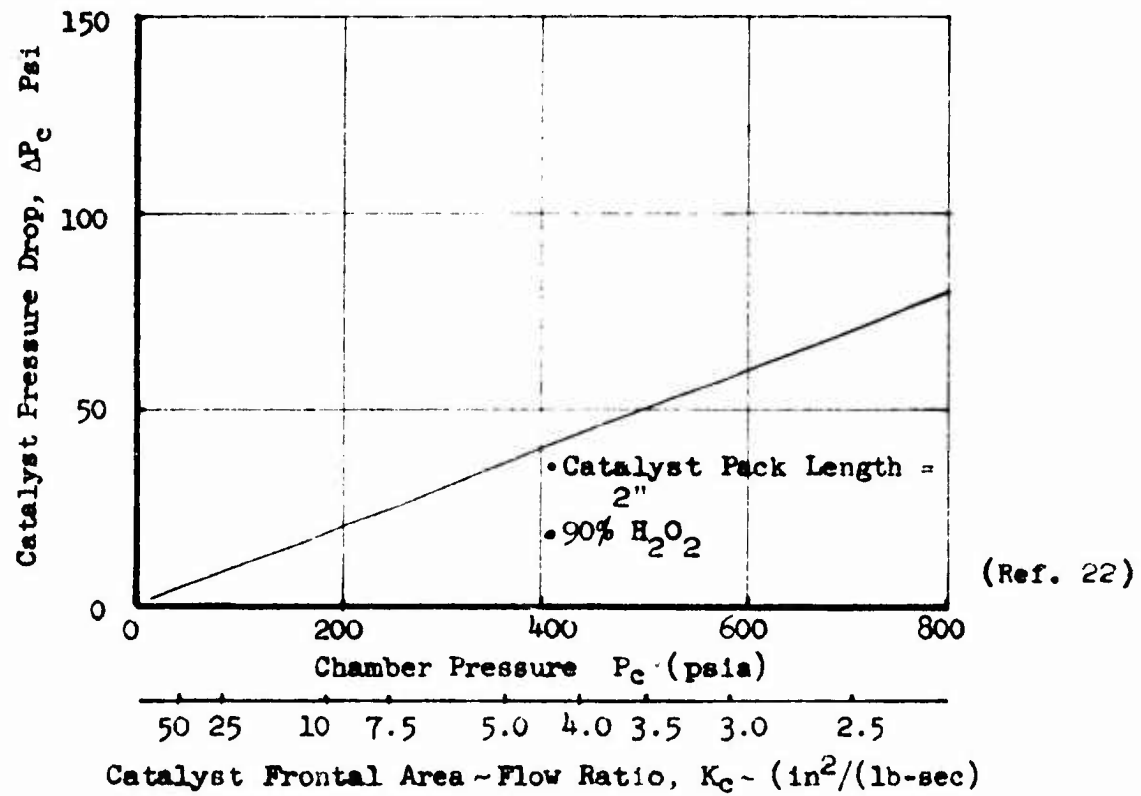


Figure 6.3-26 HYDROGEN PEROXIDE ENGINE CATALYST BED PRESSURE DROP

Hydrazine thrusters of this type can be defined in a preliminary fashion by use of the following iterative procedure (Reference 26).

- 1) Define engine thrust level, F . In velocity control engines this is done by evaluating limits to maneuver duration, acceleration, gravitational environment, control authority, engine location, and duty cycle. Maximum thrust limits are set by maximum vehicle acceleration limits for structural or control purposes, single pulse minimum maneuver velocity limits and engine system size and weight. Minimum thrust level limits are defined by maximum maneuver time limits involving engine life, performance penalties associated with finite burn-time effects, and thermal and power limits involved with being in the maneuver position.

Thrust level selection for reaction control purposes involves defining upper and lower thrust limits associated with disturbance torques, minimum impulse bit, response rate, and engine location for limit cycle operation and for all attitude positioning maneuvers.

- 2) Assume chamber pressure and nozzle expansion ratio and establish delivered specific impulse using Figures 6.3-21 and 6.3-22.
- 3) Determine propellant flow rate, \dot{w} , by:

$$\dot{w} = F/I_s \quad (\text{lb/sec}) \quad (6.3-6)$$

- 4) Assume an initial value of reactor bed loading, G (propellant flow per square inch of catalyst cross-sectional area), which can be subsequently iterated. Bed loading values can be selected between:

$$G = 0.03 \text{ to } 0.045 \text{ (lb/sec) per in}^2$$

- 5) Determine chamber diameter:

$$D_{TC} = \left[\frac{4 \dot{w}}{\pi G} \right]^{\frac{1}{2}} \quad (6.3-7)$$

- 6) Determine catalyst size at lower end of catalyst bed. It is recommended that different size catalyst pellet particles be used at various levels in the catalyst bed to promote smooth and responsive decomposition. This is the so-called "layered" catalyst consisting of discrete layers of catalyst of different sizes. For the Shell 405 spontaneous catalyst, a 0.2 to 0.3 inch deep layer of 24-30 mesh catalyst located at the upstream end of the bed is usually sufficient. The lower portion of the bed can then be made up of the 1/8 x 1/8 or 1/8 x 1/16 inch particles. The 1/8 x 1/8 size catalyst is currently the largest size available from Shell. Catalyst particle diameter (d_p) at the lower end of the bed is:

$$d_p \leq D_{TC}/8 \quad (6.3-8)$$

- 7) Evaluate the major catalyst bed parameters of bed porosity, ϵ_B , and specific surface area, A_s . Figure 6.3-27 shows catalyst bed porosity, ϵ_B , as a function of bed diameter for granular and cylindrical pellets of Shell 405 catalyst. Figure 6.3-28 shows catalyst specific surface area as a function of bed diameter for these same catalyst pellets. These figures were calculated from measured data by the following relationships

$$\epsilon_B = 1 - \left[\frac{\rho_b}{\rho_p} \right] \quad (6.3-9)$$

where: ρ_b = catalyst bed density (lb/in³)
 ρ_p = catalyst particle density (lb/in³)

Catalyst specific surface area, A_s , equals:

$$A_s = \frac{6[1 - \epsilon_B]}{\phi_s d_p} \quad (6.3-10)$$

where: ϕ_s = catalyst sphericity

Catalyst sphericity is a measure of exposed surface area on the catalyst

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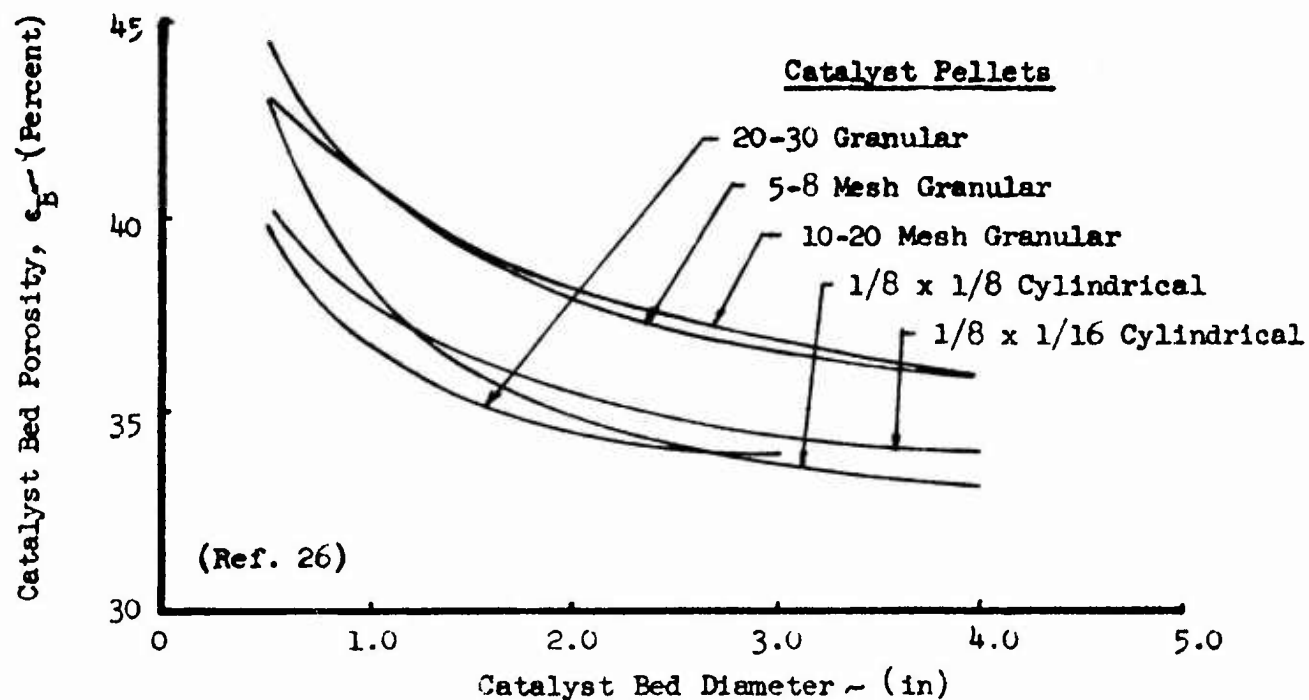


FIGURE 6.3-27 CATALYST BED POROSITY - HYDRAZINE ENGINES

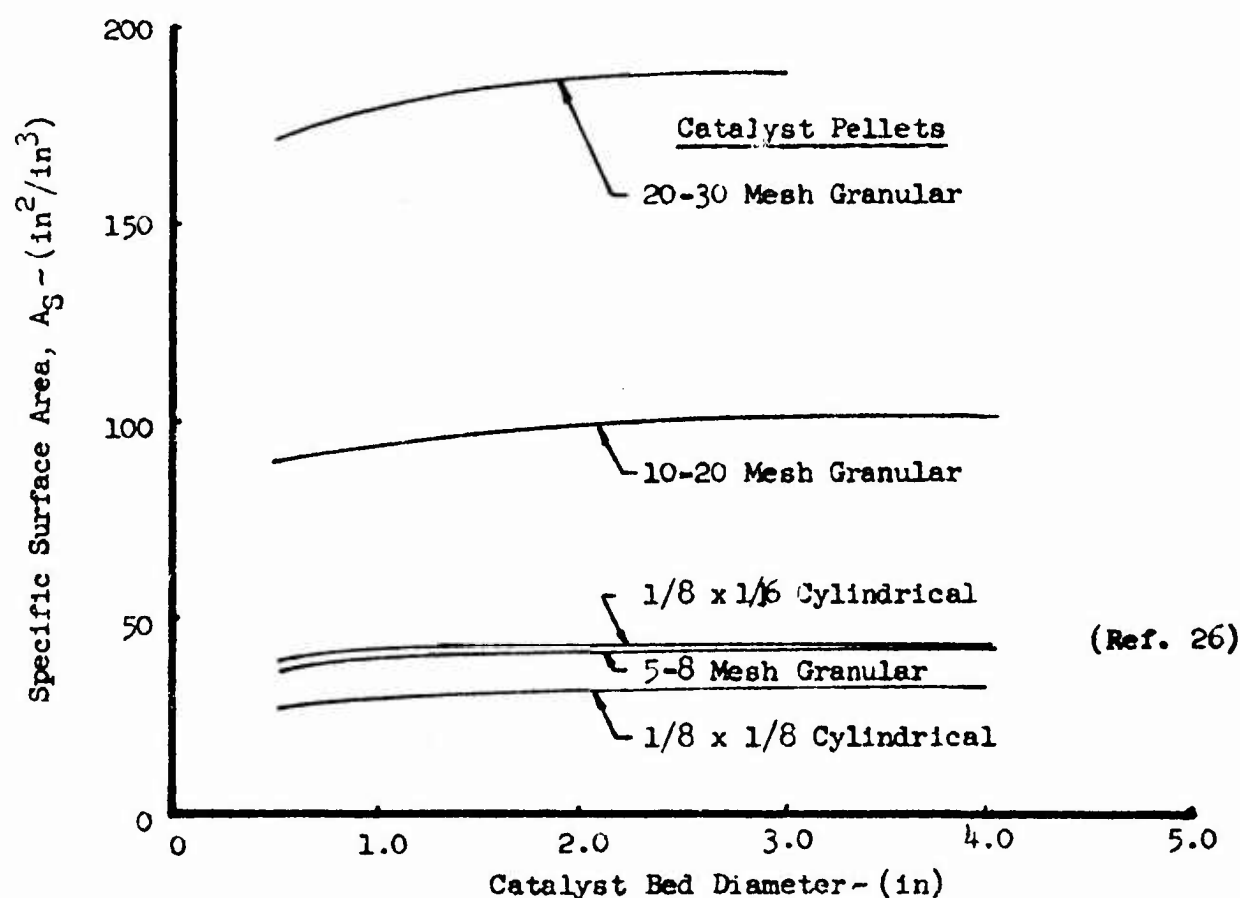


FIGURE 6.3-28 CATALYST BED SURFACE AREA - HYDRAZINE ENGINES

REV LTR _____

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| | |
|---------------|--------|
| BOEING | NO. |
| | SH 116 |

pellet. It is expressed as the ratio of exposed surface area of a sphere to that of the cylinder, where both have equal volume. Thus, for cylindrical pellets:

$$\phi_s = \frac{[1.5 D_c L_c]^{2/3}}{0.5 D_c^2 + D_c L_c} \quad (6.3-11)$$

where: $A_o/A_c = \phi_s$
 $V_o = V_c$
 D_c = cylinder diameter (in)
 L_c = cylinder length (in)
 A_o = Exposed surface area, sphere (in²)
 A_c = Exposed surface area, cylinder (in²)
 V_o = Volume, sphere (in³)
 V_c = Volume, cylinder (in³)

8) Determine catalyst bed length, L_B :

$$L_B = 0.2 + \left[145 G^{0.554} / P_c^{0.306} A_s^{0.3} \right] \quad (6.3-12)$$

where: P_c = average chamber pressure, psia

The specific surface area, A_s , is for the lower portion of the bed.

This equation represents minimum bed length for stable reactor operation, defined as less than $\pm 3\%$ P_c oscillation peak-to-peak. This results in NH_3 dissociation of approximately 55%.

9) Determine Reynolds number through each layer of the catalyst bed:

$$R_e = 5.41 [G/A_s] (10^5) \quad (6.3-13)$$

(10) Determine catalyst bed pressure drop for each particle size layer in the catalyst bed. Total bed pressure drop, which is the total for all the layers, is commonly limited to 30-40 psid.

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$$\Delta P_{CH} = \frac{1260 A_s G^{1.2} L_B^{1.8}}{\epsilon_B (1.7 P_c)} \quad \text{where: } (100 < N_T < 600) \quad (6.3-14)$$

$$\text{or } \Delta P_{CH} = \frac{3900 A_s G^2 L_B}{\epsilon_B (1.7 P_c)} \quad \text{where: } (600 < N_T < 3000) \quad (6.3-15)$$

$$(\Delta P_{CH})_T = \sum_{n=1}^{n=N} (\Delta P_{CH})_n \quad (6.3-16)$$

11) Iterate bed loading (step 4) until $(\Delta P_c)_T = 30$ to 40 psid.

Sometimes the reactor is designed as a gas generator to provide gases to remotely located thrusters, to pressurize propellant tanks, or to drive turbines. In these applications, the hydrazine decomposition reaction is usually conducted for greater ammonia dissociation, lowering gas temperatures and exhaust gas molecular weight. In these applications flow rate (\dot{w}), chamber pressure (P_c) and ammonia dissociation (X) are either specified or easily established. The catalyst bed is then designed by the above procedure, except that catalyst bed length is calculated from

$$L_B = \frac{7.83}{[10^5]} G^{0.29} \left[\frac{dp^{.32}}{\epsilon_B} \right] \left[\frac{RT_c}{\bar{m}} \right] \log_e \left[\frac{0.5}{1-X} \right] \quad (6.3-17)$$

where: dp = particle size in lower portion of catalyst bed

Injector design is a very involved subject which is strongly affected by design preferences of the engine vendors. Generally injector details are of little consequence in preliminary design exercises for spacecraft. Occasionally, however, it becomes important to configure the injector in a preliminary fashion. The following procedure for injector sizing is thus provided (Ref. 26) together with the caution that it be replaced at the earliest convenience by more exact data from the engine vendor:

- 1) Assuming a showerhead type injector, determine the necessary number of injector orifices, N_T , from catalyst bed dimensions by:

$$N_T = \frac{6A_c}{c} \quad (6.3-18)$$

where: A_c = catalyst bed cross sectional area (in^2)

- 2) Determine injector pressure drop, ΔP_i , by:

$$\Delta P_i = K_1 P_c \quad (6.3-19)$$

where: K_1 = a constant from 0.10 to 0.20

- 3) Set the injector to catalyst bed spacing at zero, and determine the orifice hole spacing by

$$S_o = \frac{\pi n D_c}{N_T + (\pi n)(n+1)} \quad (6.3-20)$$

where: S_o = spacing between orifice hole centers

n = number of injector orifice rows

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6.3.7 MONOPROPELLANT THRUSTOR GEOMETRY

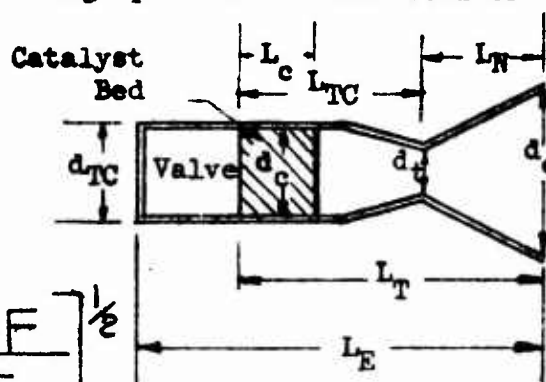
The basically different design approaches developed in 6.3.6, and extended here to cover thrustor geometry, require individual coverage for hydrogen peroxide thrustors and for hydrazine thrustors.

6.3.7.1 SIZE-HYDROGEN PEROXIDE THRUSTERS

Thrust chamber size may be developed from the procedures described in 6.1.7.1, in conjunction with the following operations referenced to Figure 6.3-27 ;

- 1) Determine catalyst pack diameter, d_c , by:

$$d_c = \left[\frac{4A_c}{\pi} \right]^{1/2} = \left[\frac{4K_c \dot{w}}{\pi} \right]^{1/2} = \left[\frac{4K_c F}{\pi I_s} \right]^{1/2}$$



(6.3-21)

- 2) Define thrust chamber exterior diameter, d_{tc} , by:

$$d_{tc} \approx 1.02 d_c \quad (6.3-22)$$

- 3) Define nozzle throat diameter, d_t , by

$$d_t = \left[\frac{4F}{\pi P_c C_F} \right]^{1/2} \quad (6.3-23)$$

- 4) Define engine major diameter, at the nozzle exit plane, d_e , by:

$$d_e = d_t [\epsilon]^{1/2} \quad (6.3-24)$$

- 5) Determine thrust chamber length, L_{TC} , by:

$$L_{TC} \approx L_c + 0.07 [F]^{1/2} \quad (6.3-25)$$

- 6) Determine nozzle length,
- L_N
- , by

$$L_N = \frac{d_t [(\epsilon)^{\frac{1}{2}} - 1]}{0.536} \quad (6.3-26)$$

- 7) Determine thruster length,
- L_T
- , by

$$L_T = L_{TC} + L_N \quad (6.3-27)$$

- 8) To define total engine assembly length, a value must be assumed for valve size, and displacement from the head end of the thruster. This factor tends to follow a relatively constant value of 4.0 inches in many installations. Thus, in numerous hydrogen peroxide engine and valve installations, engine assembly length, L_E , equals

$$L_E \approx 4 + L_T \quad (6.3-28)$$

It should be cautioned, however, that substantially smaller arrangements are possible, providing the engine assembly is specifically configured to a size constraint. In dimensionally critical applications, it is suggested that specific valve designs be used in conjunction with equation 6.3-27.

6.3.7.2 SIZE-MONOPROPELLANT HYDRAZINE THRUSTORS

Thrust chamber size may be determined with expressions developed from the design procedures previously described in 6.3.6.2. Thrust chamber exterior diameter, D_{TC} , equals approximately:

$$D_{TC} \approx \sqrt{\frac{4\dot{W}_p}{\pi G}} = \sqrt{\frac{4F}{\pi G I_s}} \quad (6.3-29)$$

Steady-state specific impulse (I_{ss}) for the probable range of applications may range from 230-234 sec. and reactor bed loading, G , from 0.03 to 0.045 lb/sec in². Thus, this expression can be reduced to:

$$D_{TC} = K_D [F]^{1/2} \quad (6.3-30)$$

where K_D = a factor between 0.35 and 0.43.

At low chamber pressures or small nozzle expansion ratios, a point is reached when chamber diameter exceeds nozzle exit plane diameter. This point occurs in monopropellant hydrazine thrusters when the reactor bed loading, G , equals the propellant flow rate per unit area at the exit plane (\dot{w}_p/A_E). Thus, when \dot{w}_p/A_E is larger than G , chamber diameter exceeds nozzle exit plane diameter, and maximum thruster diameter, D_M , equals:

$$D_M = 1.128 \left[\frac{F}{G I_{ss}} \right]^{1/2} \quad \text{when: } \left(\frac{\dot{w}}{A_E} > G \right) \quad (6.3-31)$$

When \dot{w}_p/A_E is smaller than G , nozzle exit diameter predominates and maximum thruster diameter, D_M , equals:

$$D_M = 1.128 \left[\frac{F \epsilon}{P_C C_F} \right]^{1/2} \quad \text{when: } \left(\frac{\dot{w}}{A_E} \leq G \right) \quad (6.3-32)$$

Total thruster length is comprised of the length of the installed valve assembly, the reactor and plenum, and the nozzle assembly. It is particularly sensitive to reactor length in low thrust engines which, in turn, is a strong function of the particular manufacturer's design approach. Valve dimensions are also important in small engines, and especially so because they come in discrete sizes and are rarely repackaged for particular engines. Total thruster length can be approximated with the following expression developed from numerous hydrazine thruster designs:

$$L_E = 1 + \frac{C_1}{5.06} [F]^{1/2} [(\epsilon)^{1/2} - 1] \quad (6.3-33)$$

where L_E = thruster total length, inches

C_1 = nozzle factor, equals 1.0 for conical
nozzles and 0.80 for 80% bell nozzles.

6.3.8 MONOPROPELLANT THRUSTER WEIGHT

Hydrogen peroxide and hydrazine thrusters are different enough in design and construction to merit separate discussion relating to weight definition.

6.3.8.1 WEIGHT - HYDROGEN PEROXIDE THRUSTERS

The weight of hydrogen peroxide thrusters is affected by operating chamber pressure, nozzle expansion ratio and particular catalyst bed design. In most installations, existing thruster designs are modified with basically simple changes such as adding additional catalyst screens, enlarging injector holes or screwing in new nozzle sections. Consequently, the hypothetical minimum weight hydrogen peroxide thruster rarely is used. In preliminary design exercises, it is desirable to use weight estimates which reflect hardware situations which can be realistically expected. Thus, the following expression, derived from actual hydrogen peroxide thruster design, is suggested for use in preliminary design situations:

$$W_E = .5 + .025 F \quad (6.3-34)$$

6.3.8.2 WEIGHT-MONOPROPELLANT HYDRAZINE THRUSTERS

The weight of monopropellant hydrazine thrusters is affected by the many design choices available in terms of chamber pressure, expansion ratio, bed loading, chamber geometry, cooling provisions, catalyst, and the particular

valve assembly to be used. Weight estimates can be made for preliminary design purposes using the following expression derived from many existing engine designs. Engine assembly weight, W_E , including valve, injector, chamber, catalyst, and nozzle equals approximately:

$$W_E = .3 + .05 F \quad (6.3-35)$$

6.3.9 DEVELOPED MONOPROPELLANT THRUSTORS

Monopropellant thrusters have been developed for use over a thrust range of 0.002 to 1200 pounds. Hydrogen peroxide thrusters extend from 1 to 1200 pounds within this range, though space applications have not exceeded 630 pounds. Table 6.3-3 is a list of monopropellant hydrogen peroxide engines which have been developed. Developed hydrazine engines span a thrust range of 0.002 to 300 pounds though flight applications have so far been limited to 0.02 to 50 pounds. Table 6.3-4 lists monopropellant engines developed for spacecraft applications and for research purposes.

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TABLE 6.3-3
DEVELOPED HYDROGEN PEROXIDE THRUSTORS

| THRUST (LBS) | PROGRAM | VENDOR | I _S (SEC) | P _C (PSIA) | C | NOZZLE/ CHAMBER ANGLE | DIMENSIONS (INCHES) | | | WEIGHT (LBS) | | |
|-----------------|------------------|--------|-------------------------|--------------------------|------|-----------------------------|---------------------|---------------------|---------------------|----------------------|--------------|---------------|
| | | | | | | | W/O VALVE WIDTH | W/O VALVE LENGTH | WITH VALVE WIDTH | WITH VALVE LENGTH | W/O VALVE | WITH VALVE |
| | | | | | | | | | | | | |
| 1.0 | FW 874504 | Kidde | 163 | | 30 | 0° | 1.40 | 2.60 | 1.40 | 6.5 | | 0.52 |
| 1.0 | ADV.SYNCOM | Bell | 150 | 100 | 40 | 0° | 0.50 | 2.50 | 1.25 | 6.5 | 0.23 | 0.65 |
| 1.0 | MERCURY-ACS | Bell | 156 | 276 | 15 | 0° | 2.08 | 6.62 | 2.80 | 8.3 | 0.21 | 0.70 |
| 1.5 | CENTAUR | Bell | 155 | 198 | 15 | 90° | 1.625 | 4.00 | 1.75 | 6.62 | 0.34 | 1.50 |
| 2.0 | CENTAUR | Bell | 155 | 198 | 15 | 0° | 1.625 | 4.00 | 1.62 | 6.50 | 0.32 | 1.48 |
| 2.0 | ASSET | Kidde | 150 | | 18 | | | | | | | 1.10 |
| 2.0 | SATAR | Kidde | 150 | | 18 | 90° | 0.75 | 3.00 | 1.75 | 6.775 | | 1.10 |
| 2.0 | SYNCOM COMSAT | Kidde | 156 | | 17.2 | 0° | 0.75 | 3.855 | 1.75 | 8.03 | | 0.58 |
| 2.0 | SCOUT SLV-1A | Kidde | 150 | | 22 | 90° | 2.0 | 2.5 | 3.0 | 5.0 | | 1.17 |
| 2.5 | MMU | Bell | 156 | 300 | 40 | 0° | | | 1.90 | 7.6 | 0.25 | 0.7 |
| 2.7 | SYNCOM | Kidde | 156 | | 17.2 | 0° | | | | | | 0.58 |
| 3.0 | CENTAUR | Bell | 155 | 196 | 15 | 90° | 1.625 | 4.0 | 1.75 | 6.62 | 0.35 | 1.51 |
| 3.0 | SATOR | Kidde | 150 | | 17 | 90° | 0.75 | 3.0 | 1.75 | 6.775 | | 1.00 |
| 5.0 | ADV.SYNCOM | Bell | 156 | 100 | 40 | 90° | | | 1.00 | 8.45 | 0.57 | 0.92 |
| 5.0 | ASSET | Kidde | 150 | 150 | 11.3 | 90° | 1.44 | 3.5 | 2.56 | 6.375 | | 1.00 |
| 5.0 | ATS | Kidde | 165 | | 40 | 0° | 1.0 | 5.75 | 2.50 | 9.47 | 0.80 | |
| 5.0 | ATS | Kidde | 165 | | 40 | 90° | 0.625 | 2.75 | 1.0 | 6.875 | 0.60 | |
| 5.0 | MMU | Kidde | 165 | | 40 | 0° or 90° | 1.0 | 4.0 | 2.0 | 9.37 | | 1.62 |

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TABLE 6.3-3 (Cont.)

| THRUST (LBS) | PROGRAM | VENDOR | I _S (SEC) | P _C (PSIA) | ε | NOZZLE/ CHAMBER ANGLE | DIMENSIONS (INCHES) | | | | WEIGHT (LBS) | |
|-----------------|-------------------------|--------|-------------------------|--------------------------|------|-----------------------------|---------------------|---------------------|---------------------|----------------------|--------------|---------------|
| | | | | | | | W/O VALVE WIDTH | W/O VALVE LENGTH | WITH VALVE WIDTH | WITH VALVE LENGTH | W/O VALVE | WITH VALVE |
| 5.0 | MMU | Kidde | 165 | | 40 | 0° | 0.75 | 4.09 | 2.5 | 8.12 | | 1.12 |
| 6.3 | MERCURY | Bell | 157 | 270 | 15 | 90° | 2.4 | 7.085 | 2.625 | 8.7 | .56 | 1.0 |
| 14 | MERCURY | Bell | 156 | 300 | 15 | 90° | 3.1 | 9.2 | | | 0.80 | 1.8 |
| 14 | SCOUT SLV-1A | Kidde | 150 | | 17 | 90° | 3.25 | 3.5 | 5.0 | 6.9 | | 1.98 |
| 15 | ASSET | Kidde | 150 | | 12 | 90° | 2.2 | 4.0 | 2.8 | 8.15 | | 1.75 |
| 19 | X-20 | Bell | 156 | 300 | 15 | 0° | 2.15 | 4.25 | 3.35 | 7.50 | 0.59 | 1.18 |
| 22 | Burner II | Kidde | 163 | 203 | 40 | 90° | 4.2 | 3.8 | 4.2 | 8.8 | 1.1 | 1.55 |
| 24 | MERCURY | Bell | 157 | 250 | 15 | 90° | 2.17 | 7.5 | 0.17 | 12.2 | 0.85 | 1.93 |
| 24 | SCOUT SLV-1A | Kidde | 142 | | 98 | | | | | | | |
| 34 | X-20 | Bell | 156 | 300 | 15 | 90° | 3.35 | 8.35 | 4.4 | 8.70 | 0.90 | 1.49 |
| 35 | SATAR | Kidde | 150 | | 17.7 | 90° | 3.375 | 5.4 | 3.5 | 6.14 | | 2.8 |
| 40 | ASSET | Kidde | 150 | | 12.6 | 90° | 3.45 | 4.44 | 3.45 | 9.14 | | 2.8 |
| 42 | X20-ACS | Bell | 156 | 300 | 15 | 0° | 3.35 | 9.5 | 3.35 | 10.0 | 0.91 | 1.5 |
| 43 | X15-ACS | Bell | 159 | 250 | 15 | 90° | 2.25 | 5.5 | 3.25 | 7.8 | 1.68 | 1.98 |
| 44 | SCOUT AND BLUE SCOUT | Kidde | 150 | | 12.6 | 0° | 2.31 | 5.5 | 4.02 | 8.58 | 1.49 | 4.8 |
| 48 | SCOUT SLV-1A | Kidde | 150 | | 12.6 | 120° | 2.56 | 4.0 | 4.25 | 7.5 | | 2.98 |
| 50 | CENTAUR | Bell | 158 | 154 | 15 | 0° | 2.12 | 5.05 | 3.25 | 9.36 | 1.05 | 3.05 |
| 51 | BOOST GLIDE RE-ENTRY | Kidde | 150 | 233 | 15 | 90° | 4.7 | 4.4 | 4.7 | 8.5 | 1.85 | 2.8 |
| 55 | BURNER II SESP | Kidde | 163 | 200 | 40 | 90° | 5.8 | 5.5 | 5.8 | 9.4 | 2.3 | 3.25 |

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TABLE 6.3-3 (Cont.)

| THRUST (LBS) | PROGRAM | VENDOR | I _S (SEC) | P _C (PSIA) | C | NOZZLE/ CHAMBER ANGLE | DIMENSIONS (INCHES) | | | | WEIGHT (LBS) | |
|-----------------|------------------|--------|-------------------------|--------------------------|-----|-----------------------------|---------------------|--------|------------|--------|--------------|---------------|
| | | | | | | | W/O VALVE | | WITH VALVE | | W/O VALVE | WITH VALVE |
| | | | | | | | WIDTH | LENGTH | WIDTH | LENGTH | VALVE | VALVE |
| 18-90 | LLRV | Bell | 122 | 325 | 3.0 | 0° | 3.21 | 5.25 | 4.7 | | 1.91 | 3.56 |
| 113 | X-15 | Bell | 158 | 292 | 15 | 0° | 1.9 | 5.4 | | | 1.94 | 2.3 |
| 126 | LL SIM. | Kidde | 120 | | 3.5 | 0° | 3.60 | 6.3 | 7.93 | 8.625 | | 5.6 |
| 520 | LLRV | Bell | 122 | 325 | 3.0 | 0° | 4.675 | 8.5 | | | 7.92 | 9.57 |
| 500 | SCOUT, SLV-1A | Kidde | 150 | | 9.8 | 90° | 5.5 | 7.0 | 8.05 | 12.0 | | 15.9 |
| 600 | LITTLE JOE II | Kidde | 143 | | 6.9 | 90° | 5.2 | 6.5 | 6.54 | 14.75 | | 16.85 |
| 630 | LL SIM. | Kidde | 120 | | 3.5 | | 6.75 | 8.85 | | | | 36 |
| 1200 | CO SPONS. | Bell | 157 | 250 | 15 | 0° | 8.38 | 16.0 | 8.38 | 20.8 | 22.5 | |

(Refs. 2, 3, 14, 25, 27)

TABLE 6.3-4 DEVELOPED HYDRAZINE THRUSTORS

| THRUST (LBS) | PROGRAM | VENDOR | I _s (SEC) | P _c (PSIA) | P _{in} (PSIA) | A _t (A ₁) | CATALYST | DIMENSIONS (INCHES) | | | | WEIGHT (LBS) | | IMPULSE BIT (LB-SEC) | POWER (WATTS) |
|-----------------|--------------------|-----------|-------------------------|--------------------------|---------------------------|-------------------------------------|----------|---------------------|------------|-----------|------------|--------------|------------|----------------------------|------------------|
| | | | | | | | | W/O VALVE | WITH VALVE | W/O VALVE | WITH VALVE | W/O VALVE | WITH VALVE | | |
| .05 | IR&D | R. RES. | 220 | 90 | | 50 | S-405 | 1.1 | 1.0 | 1.1 | 3.0 | 0.1 | 0.3 | | |
| .08 | SAC MOD 35 | TRW | 180 | | | | | | | | | | | .0082 | |
| .50 | USN-MRLV | R. RES. | | | | | S-405 | | | | | | | | |
| .90 | AF-MPM | R. RES. | 228 | 280 | | 100 | S-405 | 2.0 | 3.0 | 2.0 | 9.4 | 0.37 | 0.90 | 0.01 | 5 |
| 1.0 | IR&D | MARQUARDT | 230 | 180 | | 50 | S-405 | 1.8 | 3.2 | 1.8 | 5.6 | 0.5 | 0.75 | | |
| 1.0** | IR&D | HAM STD | 212 | 180 | | 40 | S-405 | 1.12 | 3.28 | 2.25 | 5.66 | 0.2 | 0.7 | | 28 |
| 1.5 | H ³ MU | R. RES. | 130* | 72 | | 90 | S-405 | 1.4 | 3.75 | | | 0.25 | | | |
| 3.0 | H ³ MU | R. RES. | 130* | 72 | | 90 | S-405 | 2.15 | 4.9 | | | 0.50 | | | |
| 3.5-1.4 | SAC MOD 35 | TRW | 229 | | | | S-405 | 1.0 | | 1.0 | | | 0.53 | 0.35 | |
| 3.5-1.2 | INTELSAT III | TRW | 229 | 250-80 | 465-115 | 50 | S-405 | 1.0 | 3.1 | 3.0 | 6.5 | 0.1 | 0.93 | 0.02 | 5 |
| 5.0 | IR&D | R. RES. | 233 | 200 | | 180 | S-405 | 2.0 | 4.01 | 1.35 | 6.75 | 0.49 | 0.88 | 0.1 | 28 |
| 5.0 | IR&D | R. RES. | 233 | 80 | | 60 | S-405 | 1.1 | 5.0 | 2.1 | 8.5 | 0.79 | 1.24 | 0.1 | 20 |
| 5.0 | LTV | R. RES. | 179 S. L. | 200 | | 1.5 | S-405 | 3.25 | 3.0 | | | | 0.95 | | |
| 5.0* | IR&D | HAM STD | | | | | | | | | | | | | |
| 5.5-2.0 | IR&D | KIDDE | 235-230 | 400-50 | | 40 | S-405 | 0.90 | 4.2 | 1.12 | 7.3 | 0.4 | | | 14 |
| 5.0 | IR&D | MARQUARDT | 232 | 155 | | 50 | S-405 | 2.4 | 6.0 | 2.4 | 8.3 | 1.2 | 1.45 | | |
| 5.0 | IR&D | MARQUARDT | | | | | | | | | | | | | |
| 8.0-2.5** | IR&D | KIDDE | 220-230 | 200-85 | | | | | | | | | | | |
| 10 | IR&D | R. RES. | 233 | 200 | | 180 | S-405 | 2.0 | 5.0 | 1.35 | 7.0 | 0.5 | 0.9 | | |
| 12.0-2.5 | IR&D | KIDDE | 232-234 | 250-50 | | | | | | | | | 1.25 | 0.05 | |
| 16-8 | IR&D | KIDDE | 234-232 | 250-50 | | | S-405 | | | | | | 1.25* | .05 | |
| 23 | BSD-PBPS | R. RES. | 230 | 150 | | 90 | S-405 | 5.0 | 5.85 | 5.0 | 8.0 | 2.7 | 3.56 | Class. | 28 |
| 23 | BSD-SAM O | HAM STD | Classified | | | | S-405 | | | | | | | | |
| 25* | MARTIN | HAM STD | | | | | | | | | | | | | |
| 25-16 | IR&D | TRW | 233-228 | 125-78 | 304-152 | 50 | S-405 | 2.73 | | 4.4 | 12.0 | | | 0.016 | |
| 27 | TRANSTAGE | R. RES. | 228 | 200 | | 50 | S-405 | 3.4 | 8.0 | 3.4 | 12.3 | 2.0 | 4.49 | 0.28 | 30 |
| 35-5 | IR&D | KIDDE | 235-230 | 300-50 | | | S-405 | 2.0 | 8.0 | | | | | | |
| 50 | NASA-JPL | R. RES. | 230 | 150 | | 90 | S-405 | 3.15 | 10 | | | 2.8* | | | |
| 50 | RANGER/ MARINER | JPL | | | | | H-7 | | | | | | 2.65 | | |
| 50** | IR&D | JPL | | | | | S-405 | | | | | | | | |
| 50 | MARINER 69 | TRW | | | | 44 | S-405 | | | | | | 2.5 | | |
| 60-12 | IR&D | KIDDE | 220-211 | 270-80 | | | | | | | | | 2.8 | 0.60 | |
| 75 | RPL | R. RES. | Classified | | | 50 | S-405 | 3.3 | 6.0 | | | | 2.81 | Class | 28 |
| 75** | IR&D | TRW | 230 | | | | S-405 | | | | | | | 0.75 | |
| 75* | IR&D | HAM STD | | 185 | | 60 | S-405 | 4.27 | 9.84 | 4.27 | 17.2 | 4.7 | 6.6 | | 40 |
| 100 | IR&D | HAM STD | | | | | | | | | | | | | |
| 100* | IR&D | HAM STD | | | | | | | | | | | | | |
| 100 | IR&D | MARQUARDT | 236 | 165 | | 50 | S-405 | 5.5 | 11.0 | 5.5 | 14.0 | 6.12 | 7.21 | | |
| 150 | IR&D | HAM STD | | 225 | | 80 | S-405 | 5.45 | 12.0 | 5.45 | 19.0 | 7.3 | 9.2 | | 40 |
| 170 | IR&D | R. RES. | 236 | 170 | | 180 | S-405 | 8.5 | 17.5 | 8.5 | 23.0 | 9.0 | 13 | 280 QR | |
| 200* | IR&D | HAM STD | 235 | 250 | | 80 | S-405 | 6. | 12.94 | 6. | 20.2 | | 10.7 | | 40 |
| 240-12 | IR&D | KIDDE | 225-217 | 220-80 | | | S-405 | 4.5 | 9.38 | | | | | | |
| 287-16 | AF-612 | TRW | 235 | 229-13 | 500-14 | 90 | HA3-S405 | 5.1* | 15.8** | 8.4 | 24 | 19.0 | | 150 QR | 2000W |
| 300 | IR&D | R. RES. | 232 | 300 | | 70 | S-405 | 6.7 | 15 | 6.7 | 19 | 34.0 | 39 | | |

LEGEND:

* N₂H₄ + H₂O** N₂H₄ + N₂H₅NO₃ + H₂O

+ HEAVY WEIGHT

** ATE-80

S.L. SEA LEVEL

QR QUAD REDUNDANT VALVE

H³MU HYDRAZINE HAND HELD MANEUVERING UNIT

(Refs. 14, 16, 20, 28)

6.4 BIPROPELLANT THRUSTORS

6.4.1 GENERAL

Liquid bipropellant engines produce thrust by chemically reacting two propellants, called the oxidizer and the fuel, in a thrust chamber and directing the resulting exhaust through a nozzle. Bipropellant engines are used in the Lunar Orbiter, Surveyor, Agena, Mercury and Apollo spacecraft.

Early bipropellant engines employed hydrogen peroxide, liquid oxygen or nitric acid as "oxidizers" with alcohol, anilene, or kerosene "fuels". These engines were used in missiles, rocket-powered aircraft, and boosters.

Satellites have only recently used bipropellant engines to any extent. These applications have occurred in conjunction with the trend to the so-called "earth-storable" propellants. Spacecraft applications strongly contributed to this trend by using the good storability and performance characteristics of these propellants to advantage in the space environment.

Bipropellant engines for spacecraft generally use nitrogen tetroxide (N_2O_4) or mixed oxides of nitrogen (MON) as oxidizers and Aerozine-50 or monomethylhydrazine (MMH) as fuels. Occasionally, inhibited red fuming nitric acid (IRFNA) is used as an oxidizer, and "neat" hydrazine (N_2H_4) or unsymmetrical dimethylhydrazine (UDMH) are used as fuels. MON is a mixture of nitrogen tetroxide with 10-25% nitric oxide. Aerozine-50 is a trade name for a 50-50 mixture, by weight, of hydrazine and UDMH. Chlorine trifluoride (ClF_3) is increasing in use with the fuels mentioned. Beyond these propellants a generation of higher-energy, storable propellants is envisioned which includes the boranes, "Compound A", Hybaline", and similar compounds. However, a real need for these propellants has yet to be established. Consequently, this section will cover the currently popular nitrogen tetroxide, IRFNA, MON, and chlorine

trifluoride oxidizers, and hydrazine, UDMH, NCH, and Aerosine-50 fuels.

Combinations of these fuels and oxidizers are hypergolic, that is, they ignite on contact in the thrust chamber and require no auxiliary ignition provisions. This is desirable from the standpoint of system simplicity but it complicates service and handling procedures in that inadvertent contact of fuel to oxidizer must be avoided.

6.4.2 OPERATING PRINCIPLE

Bipropellant rocket engines consist of a propellant control valve, propellant supply lines, injector, thrust chamber, and nozzle assembly. Provisions may also be included to mount the engine to the spacecraft to maintain a predetermined thermal condition, (thermal control) and to control the engine thrust vector direction (TVC).

Propellants are provided to the engine injector on demand by propellant flow control valves in both the fuel and oxidizer engine feed lines. Fuel and oxidizer are kept separate continuously as they pass through the engine propellant manifold into, and through the injector assembly. The injector distributes and mixes fuel and oxidizer within the chamber to promote efficient reaction, to prevent and suppress pressure instabilities, and to assist in engine cooling.

Chemical reaction of these bipropellants produces gases at high temperatures (5500-6000°R) which exceeds the structural capabilities of practical chamber materials. Propellant mixture ratio (ratio of oxidizer to fuel, by weight, at the chamber walls is deliberately controlled by injector design so that substantially cooler, fuel-rich gases contact the walls. Heat rejection from

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bipropellant engines is controlled by radiation, material ablation, or by regenerative cooling. Almost all early bipropellant engines used regenerative cooling or material ablation to protect the engine during, and immediately following, engine operation. Regeneratively cooled engines are not commonly used where rapid response and pulsing capability are desired because of the large hold-up volume involved. Ablative engines have been used for some time, so the technology has reached a considerable degree of refinement. But, ablative engines are life limited by ablation rate and the amount of ablative material which means that long operating periods require heavier engines. Some radiation cooling has been used in later ablative engine designs to reduce weight. Radiation cooled bipropellant engines have recently been used with success in space. The bipropellant Marquardt MA-109 engine has been successfully flown in the five Lunar Orbiter missions. Radiation cooled engines are fairly lightweight, much less sensitive to life limitations, and can be closely coupled to the propellant valves for fast response and good pulsing performance. Radiation cooled, bipropellant, engine designs currently cover the 5 to 2000 lb. thrust range, and this trend to radiation cooling is expected to continue. Ablative engine designs persist, especially in the larger bipropellant engines which are sometimes augmented with some radiation cooling. The Surveyor spacecraft is the only currently known use for low thrust, regeneratively-cooled, bipropellant engines. Table 6.4-1 shows a comparison of these bipropellant engine types based on those factors which are particularly mission or spacecraft related.

| CONSIDERATION | CHAMBER TYPE | | |
|----------------------------------|--------------|--------------|-----------|
| | ABLATIVE | REGENERATIVE | RADIATION |
| WEIGHT - THRUST CHAMBER | | BEST | * |
| - OVER-ALL SYSTEM | GOOD | ** | * GOOD |
| RESPONSE | GOOD | | GOOD |
| PERFORMANCE (TRAPPED PROPELLANT) | GOOD | | GOOD |
| THROTTLING ABILITY | GOOD | *** | GOOD |
| SHORT DEVELOPMENT TIME | BEST | | |
| COST | BEST | | |
| ENVIRONMENTAL - METEORITE DAMAGE | BEST | | |
| - HARD VACUUM | | GOOD | GOOD |
| - RADIATION | | GOOD | GOOD |
| VEHICLE COMPATIBILITY | GOOD | GOOD | |

* WEIGHT COMPARISON DEPENDS ON THRUST LEVEL

** JACKET PRESSURE DROP INCREASES TANK PRESSURE FOR PRESSURE-FED SYSTEMS

*** REASONABLE RANGE OBTAINABLE WITH H₂

TABLE 6.4-1 BI-PROPELLANT THRUST CHAMBER COMPARISON

(Courtesy Rocketdyne Div., North American/Rockwell)

6.4.3 BI-PROPELLANT THRUSTER CONSTRUCTION

The three major cooling techniques used in small bipropellant engines involve regenerative cooling, materials ablation or radiation cooling. Ablative engines are particularly life limited by the amount of ablative material present. Ablative and regeneratively cooled thrust chambers have low exterior surface temperatures (normally less than 500°F) which permits them to be recessed within the spacecraft. Radiation cooled engines (surface temperatures above 2000°F) are usually not recessed since they induce heavy thermal loads on adjacent equipment. Sometimes they are even affixed to extended mounts as a thermal standoff to minimize radiation effects. These mounts, plus associated plumbing and wiring can, however, impose significant weight penalties to the system. Recently research and development programs have been conducted to adapt radiation cooled bipropellant chambers to buried installations.

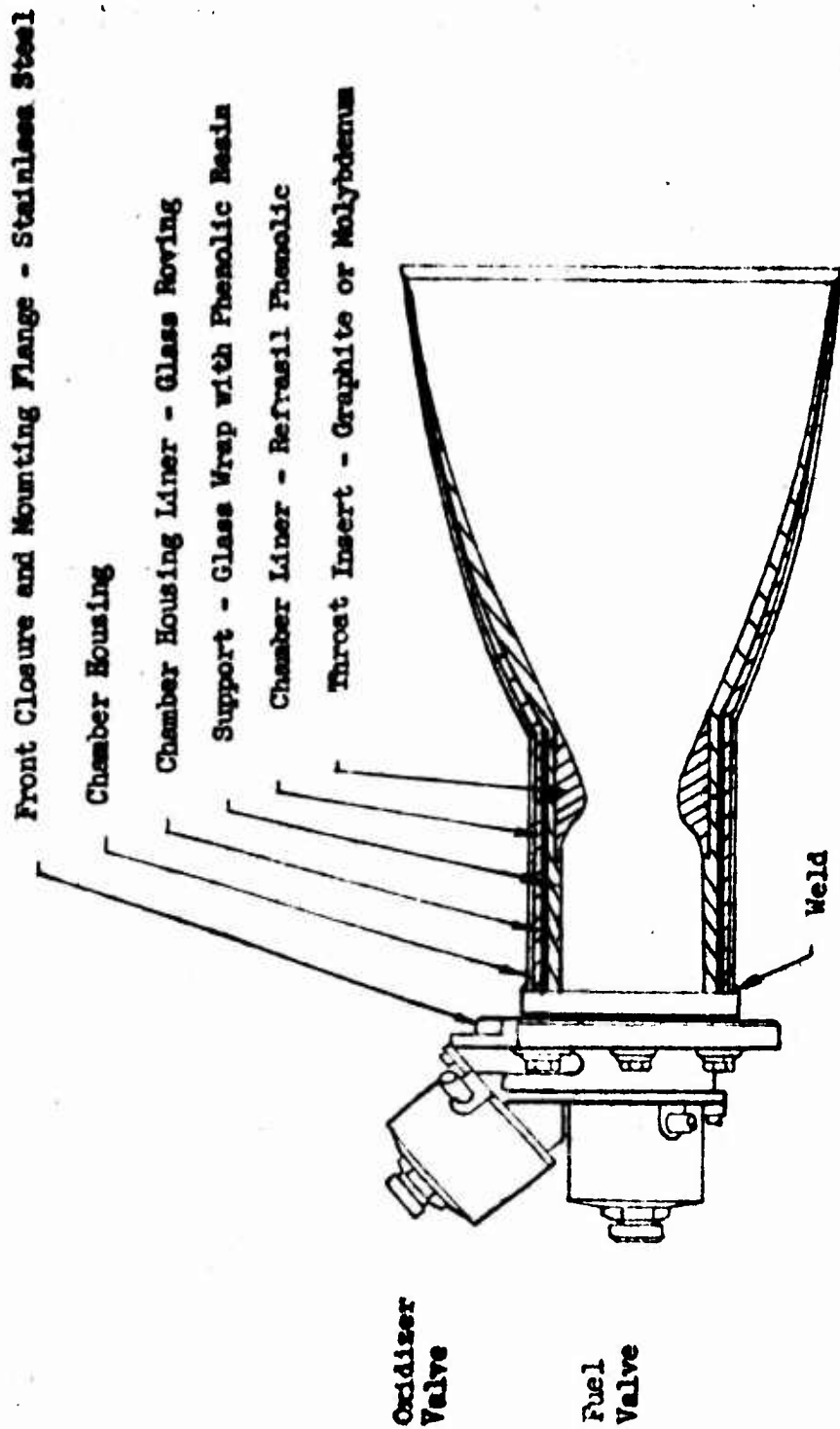
6.4.3.1 ABLATIVE ENGINES

A typical ablative engine is shown in Figure 6.4-1 complete with valves.

In simplified terms, an ablative thrust chamber is constructed of resin-impregnated fiberglass. Cooling is accomplished by boiling out the resin. This type thrust chamber assembly has been employed on the Gemini, Apollo Command Module, and the Titan III Transtage. Ablative thrust chambers are used with radiation cooled nozzle extensions in larger propulsion units (8000-20000 lb-thrust class).

Ablative thrust chambers are usually designed for chamber pressures between 100 to 130 psia since pressure related weight penalties become prohibitive at higher pressure levels. Above a pressure level of 130 psia, a refractory-type throat insert is considered mandatory to minimize thrust variations due to throat area growth. A somewhat common design criteria involves restricting

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Ablative Bipropellant Engine

Figure 6.4-1

external surface temperature below 400°F to permit a buried installation.

6.4.3.2 RADIATION COOLED ENGINES

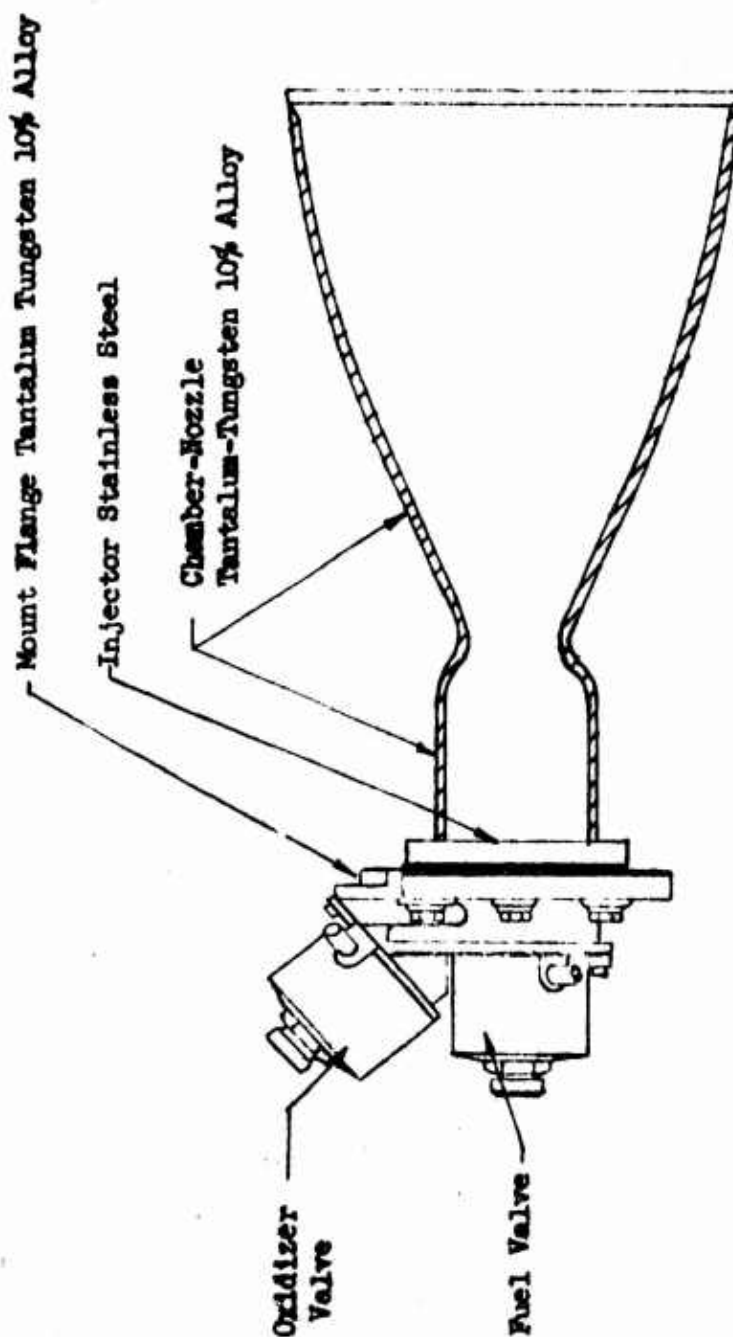
A typical radiation cooled bipropellant engine is shown in Figure 6.4-2.. Engines similar to this are used on Lunar Orbiter, Apollo Service and Lunar modules, and on the Agena secondary propulsion system. The high combustion temperatures of bipropellant engines require special materials including the refractory metals. Currently, the most frequent applications involve molybdenum-titanium or tantalum-tungsten alloys. Government funded research and development efforts are currently being conducted to apply columbium alloy and beryllium metals to thrust chamber construction.

Radiation cooled thrust chambers are coated with materials (such as an aluminide or silicide) to prevent oxidation of the base metal. External surfaces are also coated to improve emissivity, and to prevent oxidation during test. Currently, these coatings limit chamber wall temperatures to about 3000-3200°F, which in turn limits maximum chamber pressure to about 100 psia. Current operational throat temperatures are on the order of 2000-2500°F, a value achieved by operating the engine slightly off optimum mixture ratio and/or the incorporation of film cooling. A considerable margin is generally maintained between actual and allowable wall temperature to provide long engine life.

6.4.3.3 REGENERATIVELY COOLED ENGINES

A typical regeneratively cooled, small bipropellant engine is shown in Figure 6.4-3. . At this time, the only known application of this principle is on the Surveyor spacecraft vernier engines. This spacecraft uses three radially distributed engines for midcourse correction, attitude control retro maneuvers, and terminal maneuver vernier control. Attitude control is accomplished by differential throttling.

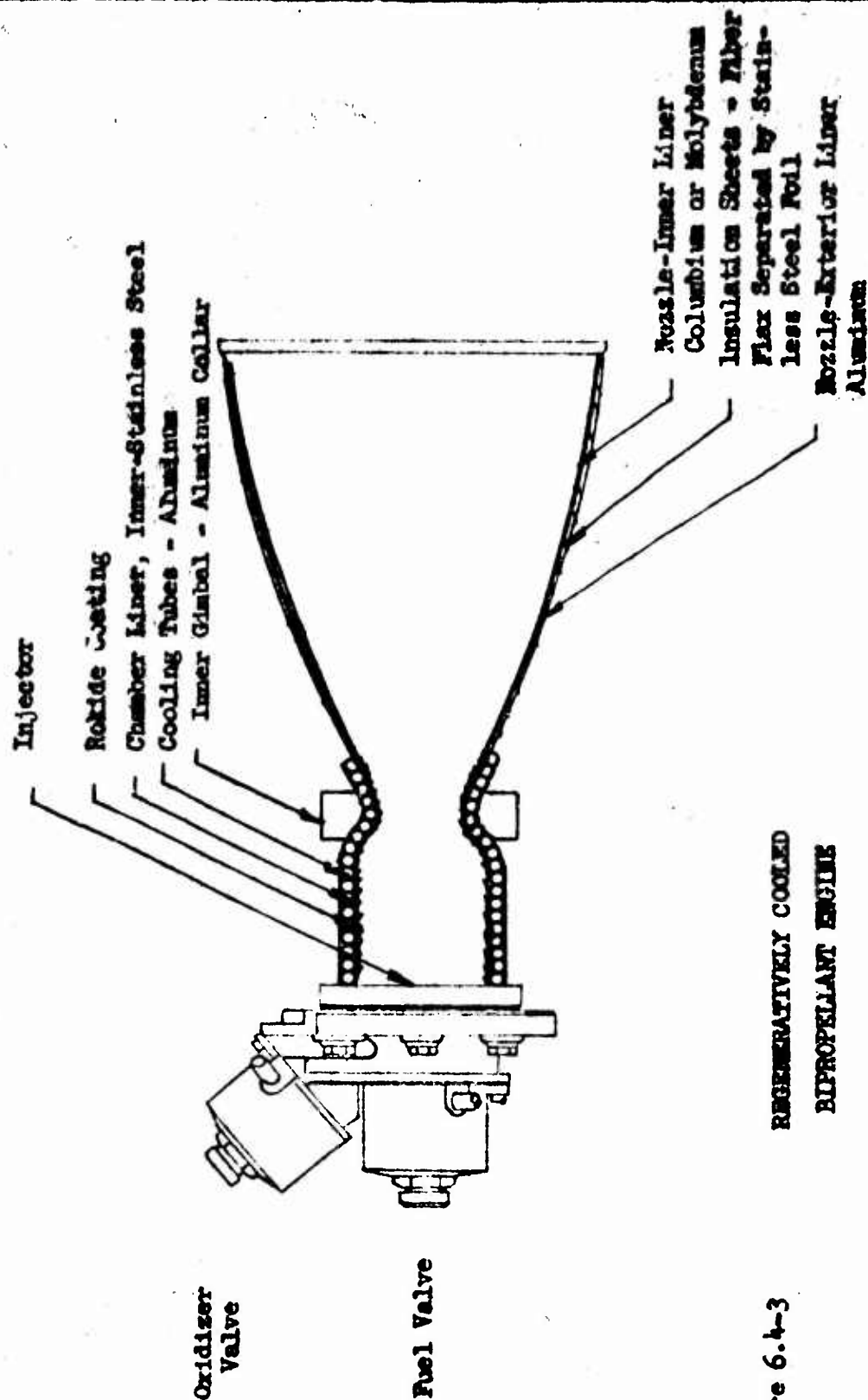
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RADIATION COOLED
BIPROPELLANT ENGINE

Figure 6.4-2

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REGENERATIVELY COOLED
BIPROPELLANT ENGINE

Figure 6.4-3

The regenerative cooling circuit contributes a relatively large trapped propellant volume below the engine control valve. This prolongs engine operation during any valve actuation until the cavity is cleared. Thus, transient response and minimum operating times are inferior to those possible in the more closely coupled ablative or radiation cooled engines. It is possible to design regenerative engines specifically for transient performance by locating the propellant flow control valve between the jacket and the injector. However, post-firing heat soakback becomes a significant problem in this case if it can cause the propellants to boil. This is not desirable in that it may overpressurize propellant plumbing briefly, and it may result in entrained gas problems during subsequent operation.

6.4.4 BIPROPELLANTS

Bipropellants in extensive space usage currently involve the so-called "earth storable" propellants. Common oxidizers are nitrogen tetroxide and the mixed oxides of nitrogen (MON), nitric acid. Chlorine trifluoride, already in Navy shipboard use, may also be used in space application. Common fuels are hydrazine, unsymmetrical dimethylhydrazine, Aerozine-50, and monomethylhydrazine. Significant physical properties of these propellants are summarized in Table 6.4-2. They will be discussed separately in greater detail.

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TABLE 6.4-2

PHYSICAL PROPERTIES
OF PROPELLANTS

| <u>Oxidizers</u> | <u>Freeze Point, °F</u> | <u>Boil* Point, °F</u> | <u>Specific* Gravity</u> | <u>Absolute* Viscosity, lb/ft-sec</u> | <u>Specific* Heat, Btu/lb-°F</u> |
|------------------|---------------------------------|--------------------------------|------------------------------|---|--|
| N_2O_4 | 11.8 | 70 | 1.49 | 2.95×10^{-4} | 0.365 |
| MON-10 | -10 | 45 | 1.46 | 2.04×10^{-4} | |
| MON-15 | -24 | 35 | 1.41 | | |
| MON-25 | -61 | 17.5 | 1.39 | | |
| IRFNA | -65 | 142 | 1.59 | 9.50×10^{-4} | 0.418 |
| ClF_3 | -118 | 53 | 1.83 | 3.10×10^{-4} | 0.308 |
| <u>Fuels</u> | | | | | |
| N_2H_4 | 34 | 236 | 1.00 | 6.90×10^{-4} | 0.734 |
| UDMH | -71 | 146 | 0.785 | 4.10×10^{-4} | 0.647 |
| MMH | -62.3 | 189 | 0.871 | 6.70×10^{-4} | 0.699 |
| Aero-50 | 18.8 | 158 | 0.908 | 7.10×10^{-4} | 0.689 |

* Boiling temperature, referenced to 14.7 psi

+ Specific gravity, viscosity, and specific heat referenced to 60°F

(Ref. 4)

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6.4.4.1 OXIDIZERS-NITROGEN TETROXIDE AND THE MIXED OXIDES OF NITROGEN

Nitrogen tetroxide (N_2O_4) consists principally of the tetroxide in equilibrium with a small amount of nitrogen dioxide (NO_2). As obtained commercially, it contains less than 0.1% water by weight. Nitrogen tetroxide is very reactive and toxic, but is not sensitive to mechanical shock, heat, or detonation. Specific heat, absolute viscosity, density and vapor pressure of nitrogen tetroxide are shown as functions of temperature in Figure 6.4-4.

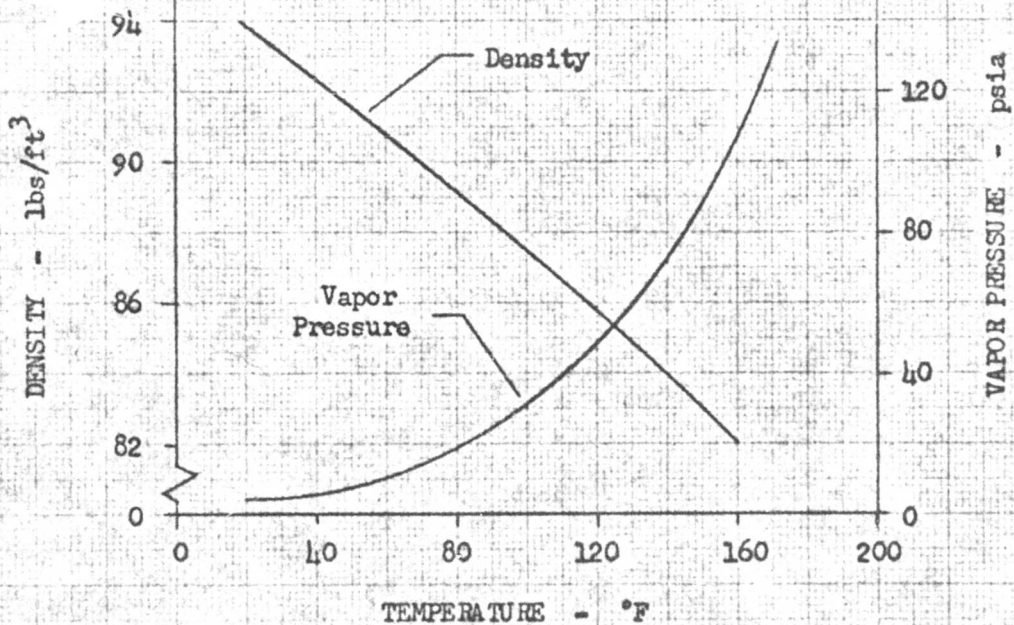
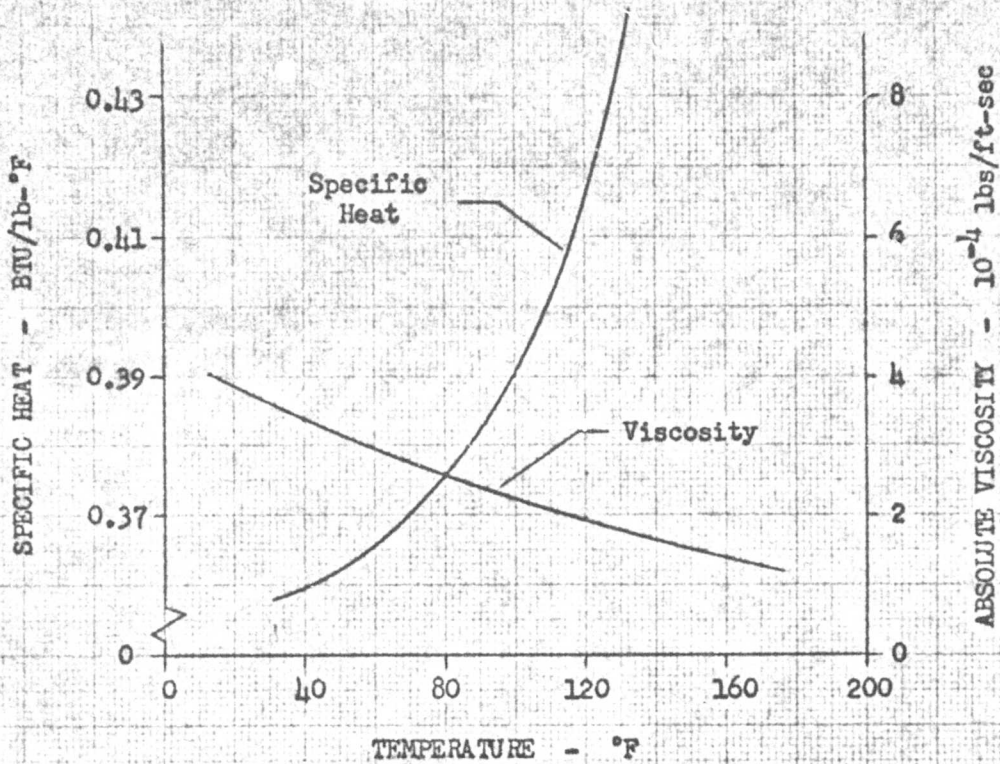
The relatively high freezing temperature of nitrogen tetroxide may be reduced by forming a solution with nitric oxide (NO), producing the so-called "mixed oxides of nitrogen" or MON. These solutions are generally designated by the percentage of NO, hence MON 10, MON 15, and MON 20. Boiling point is also changed, as indicated in Table 6.4-2. The density, absolute viscosity and vapor pressure of MON 10 solutions are shown in Figure 6.4-5.

6.4.4.2 Oxidizer-Nitric Acid

Inhibited red fuming nitric acid (IRFNA) consists of 83.4% nitric acid (HNO_3), 13% nitrogen tetroxide (N_2O_4), 3% water and 0.6% hydrogen fluoride (HF). It is highly corrosive, toxic, and reacts with most metals and organic materials. It is currently being employed in several launch vehicle stages, such as Agena, and in several air-launched missiles. Figure 6.4-6 shows specific heat, absolute viscosity, density, and vapor pressure of IRFNA as a function of temperature.

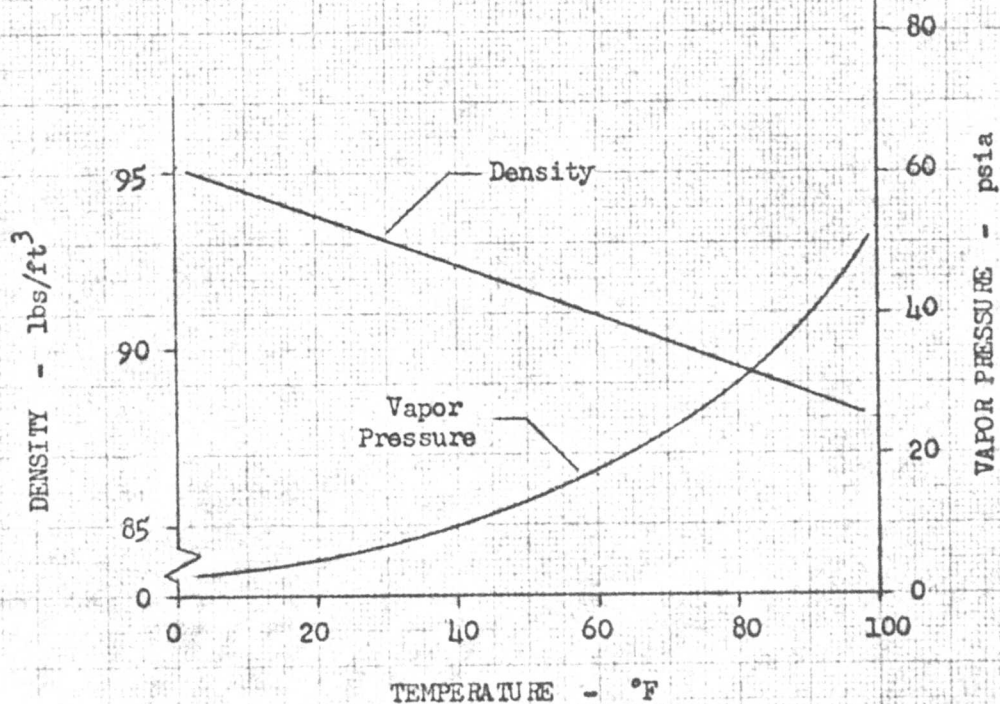
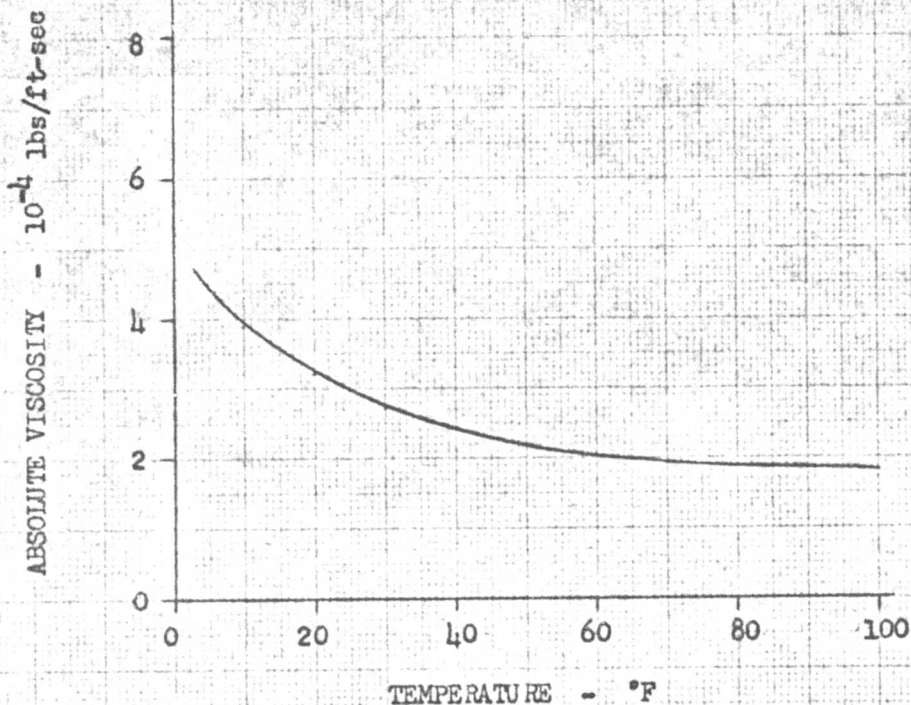
6.4.4.3 Oxidizers-Chlorine Trifluoride

Chlorine trifluoride (ClF_3) is commercially available with purities greater than 99%. It is a toxic and corrosive oxidizing agent similar to fluorine. It reacts with water and will support combustion with almost all organic vapors and liquids. It reacts with all elements except the rare gases and nitrogen. However, it forms a protective film on certain metal surfaces which



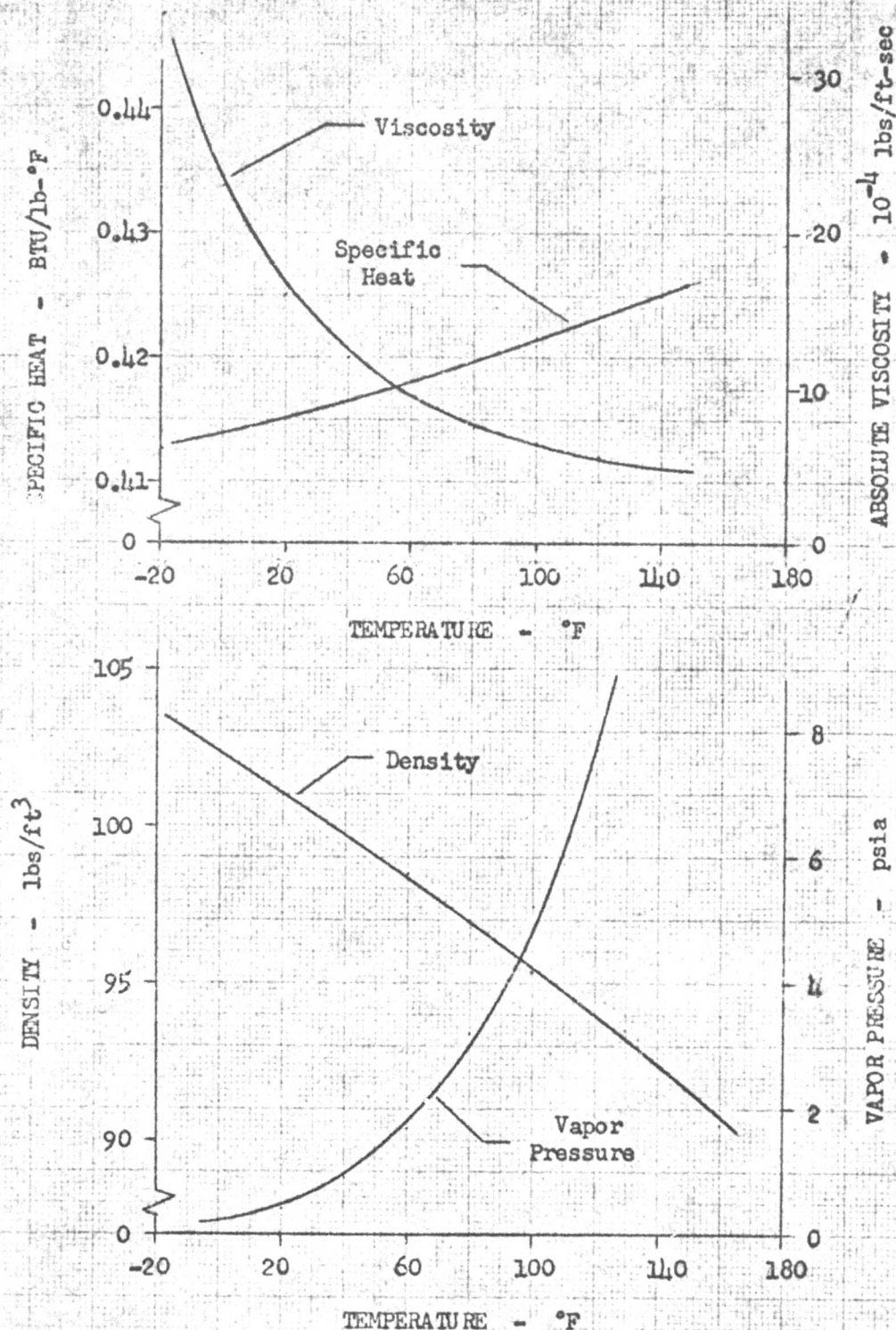
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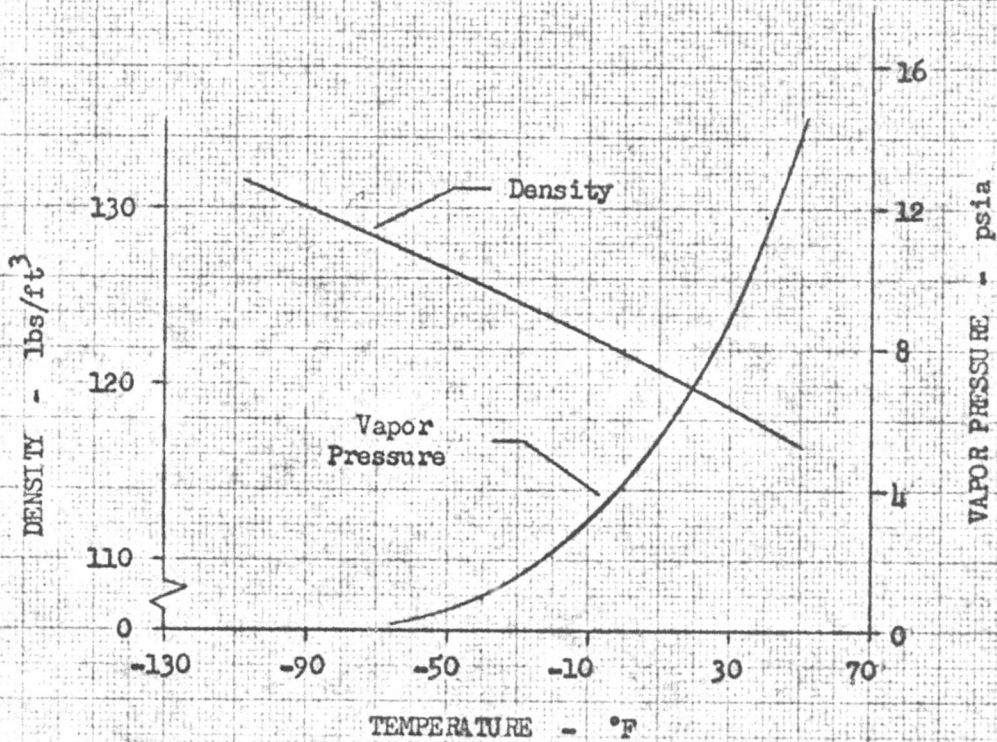
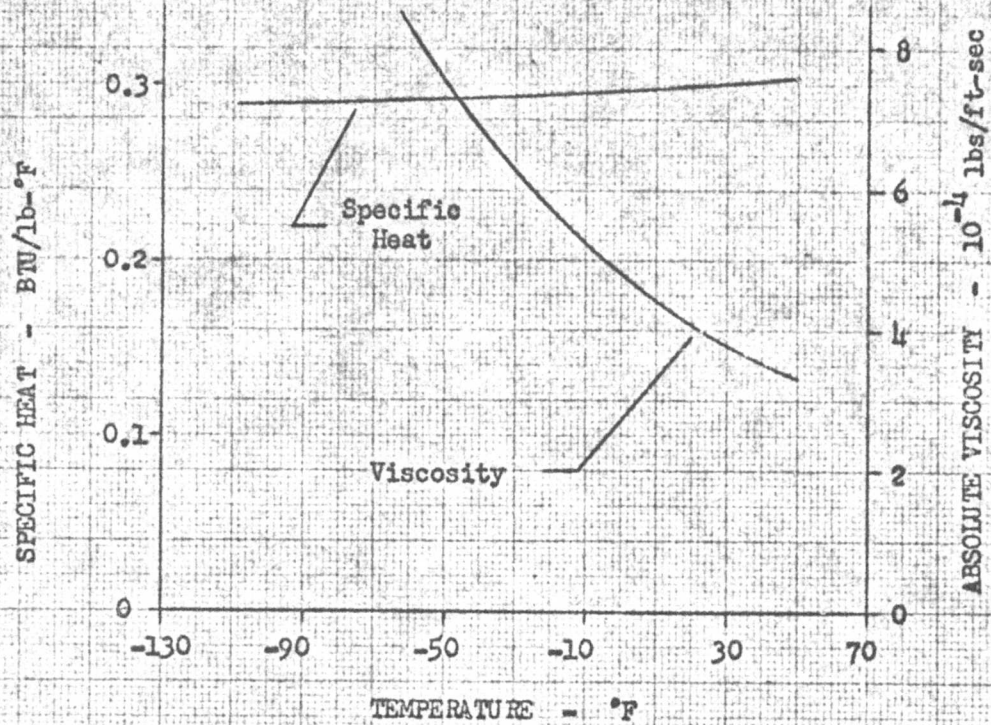
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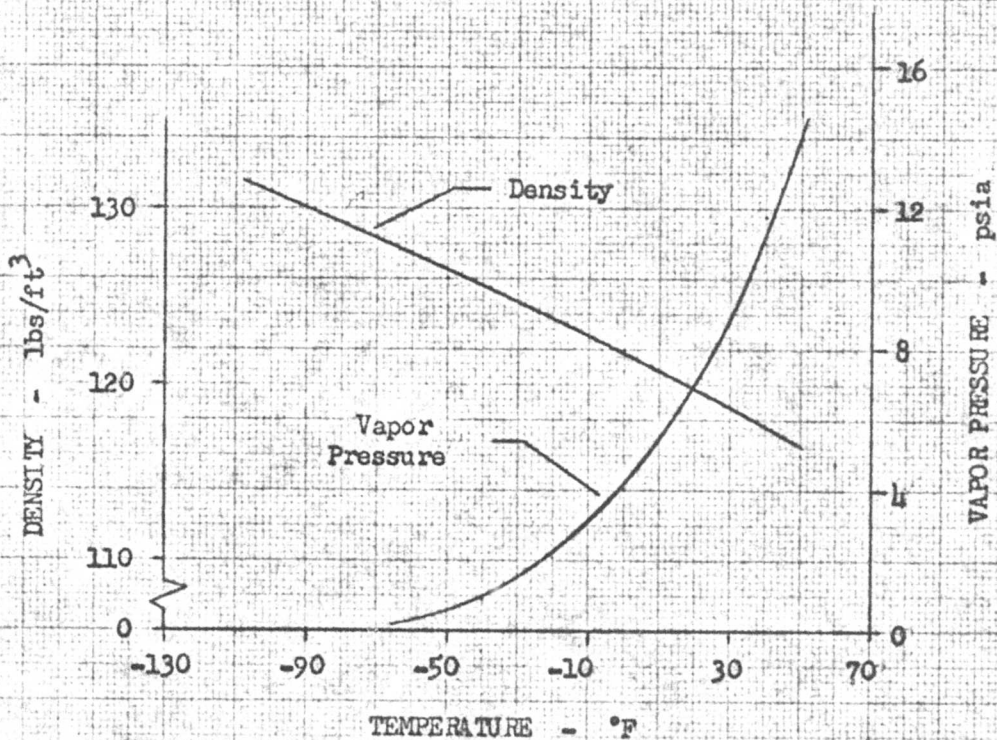
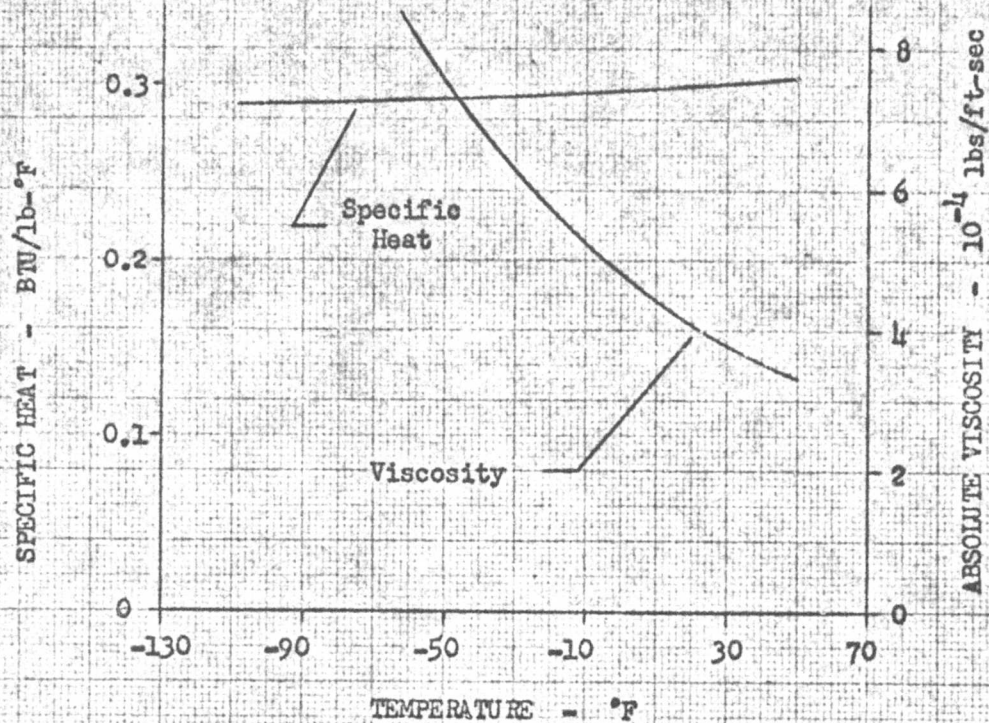
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PHYSICAL PROPERTIES
CHLORINE TRIFLUORIDE

THE BOEING COMPANY

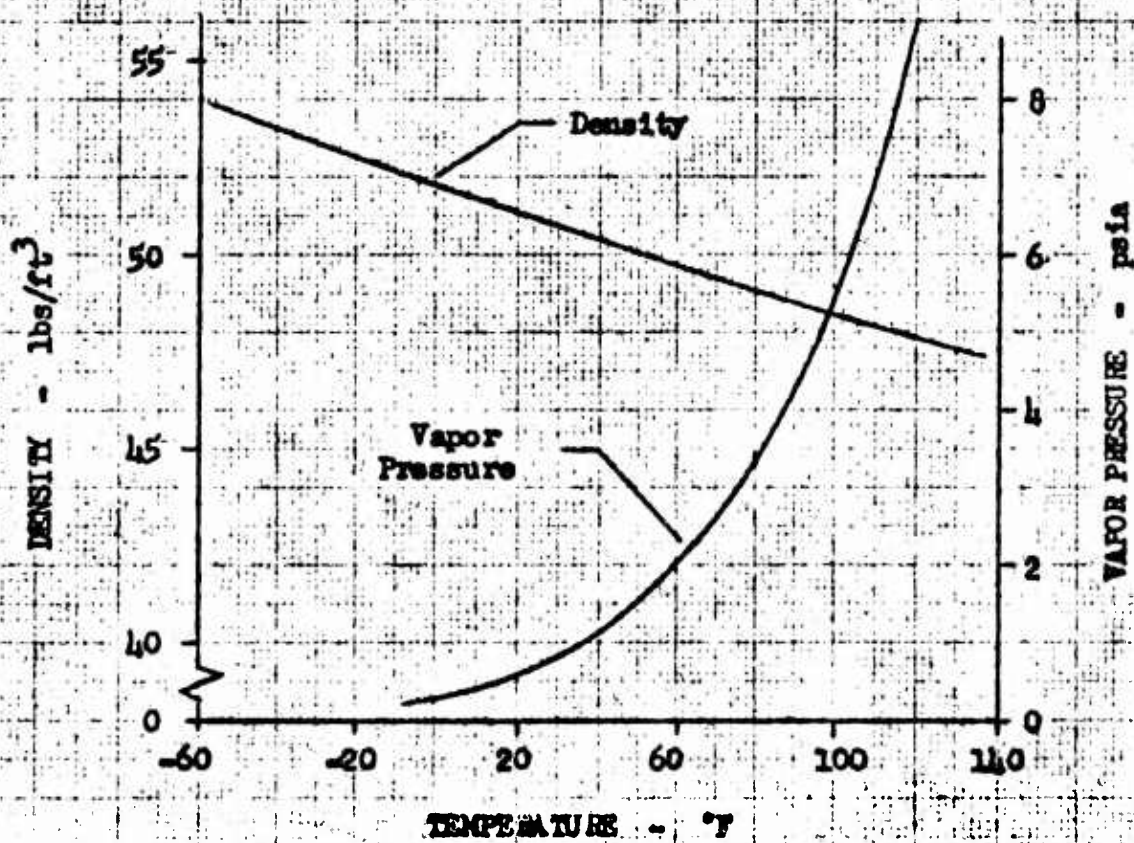
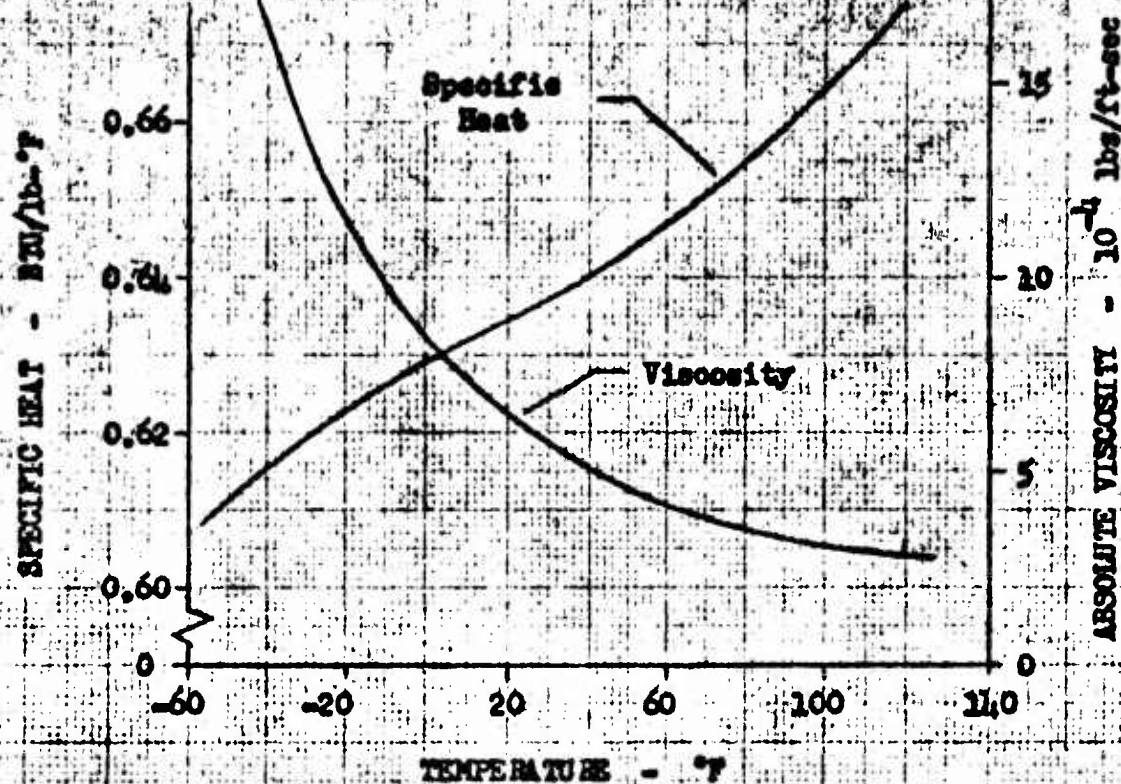
FIGURE
6.4-7

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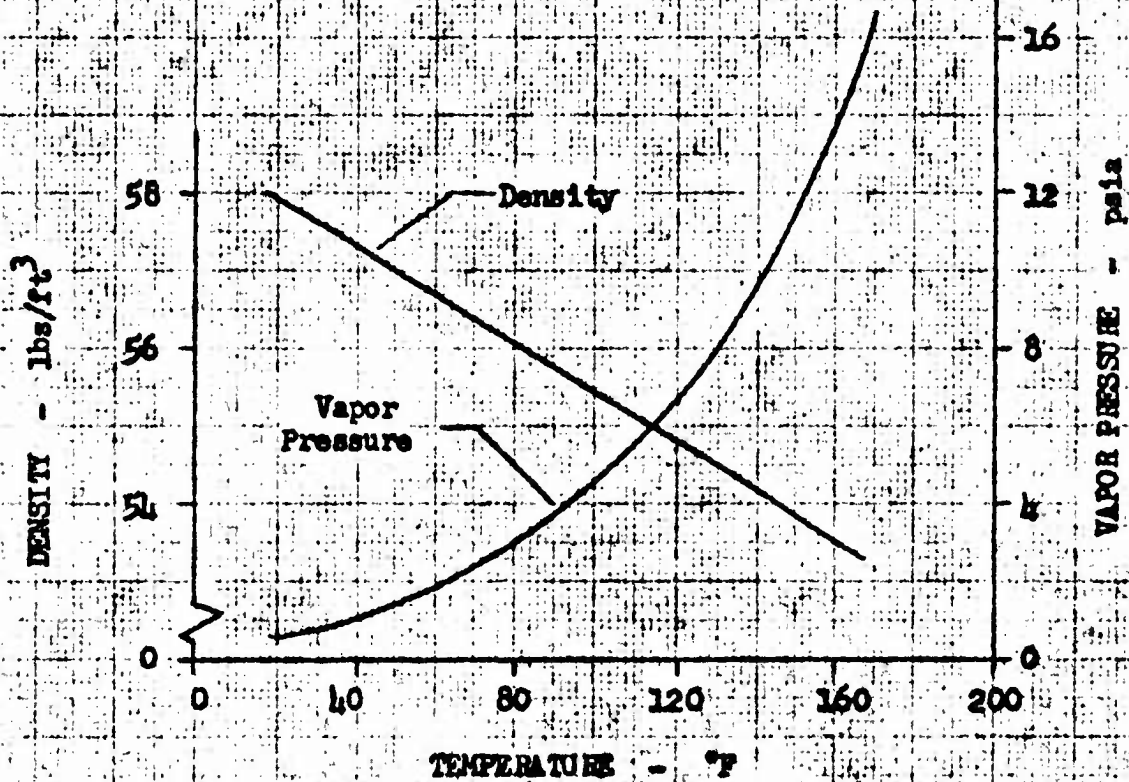
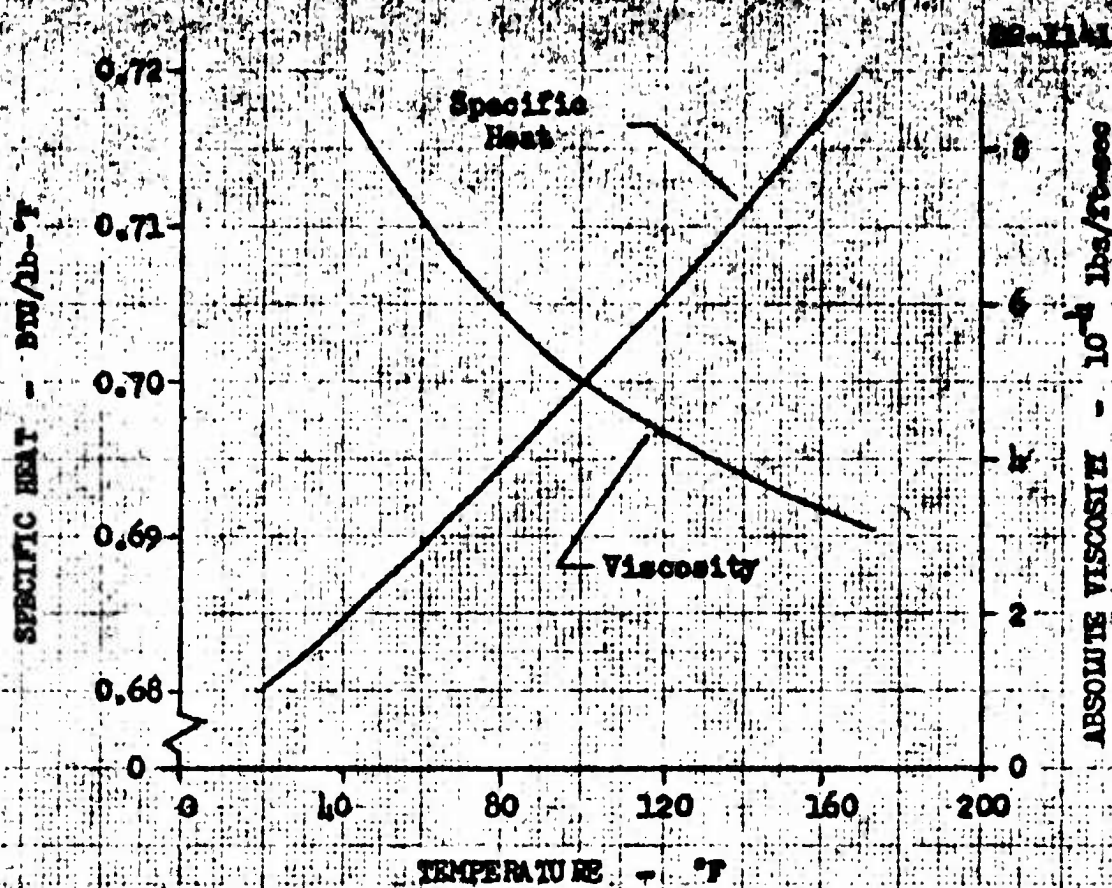
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(Fig. 4)

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PHYSICAL PROPERTIES
AEROXINE-50

THE BOEING COMPANY

PAGE
147

6.4.4.7 FUELS-MONOMETHYLHYDRAZINE (MMH)

As with other hydrazine-type fuels, MMH is toxic and volatile. It is not sensitive to impact or friction. It is more stable than hydrazine, but is similar to hydrazine in sensitivity to catalytic decomposition. The viscosity, specific heat, density and vapor pressure of MMH is shown in Figure 6.4-10 as a function of temperature.

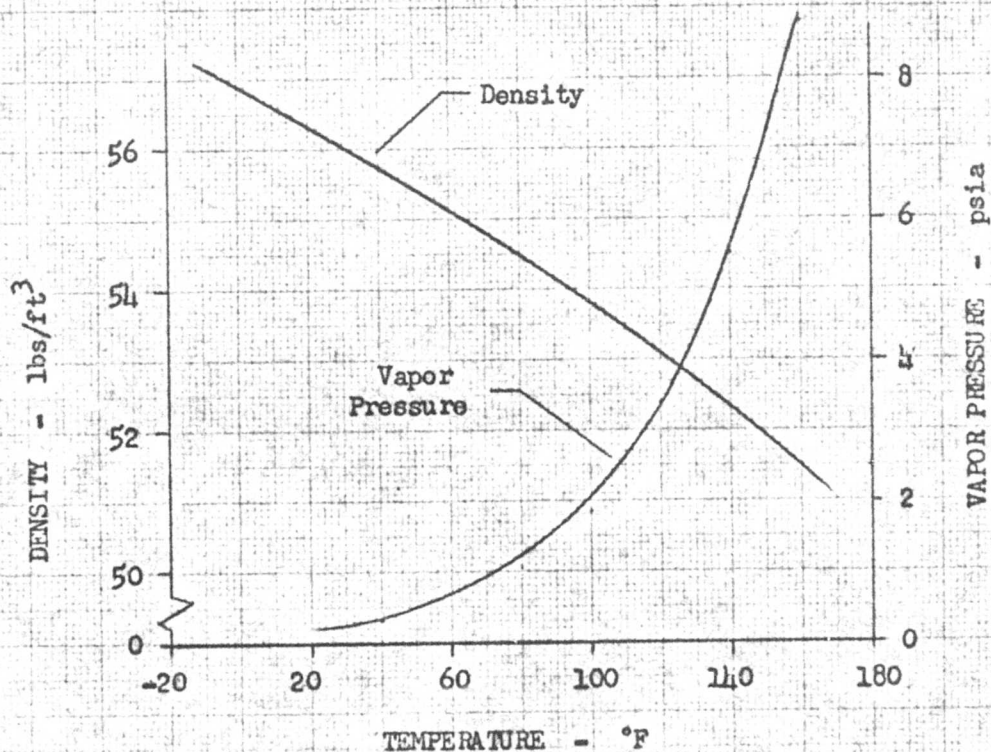
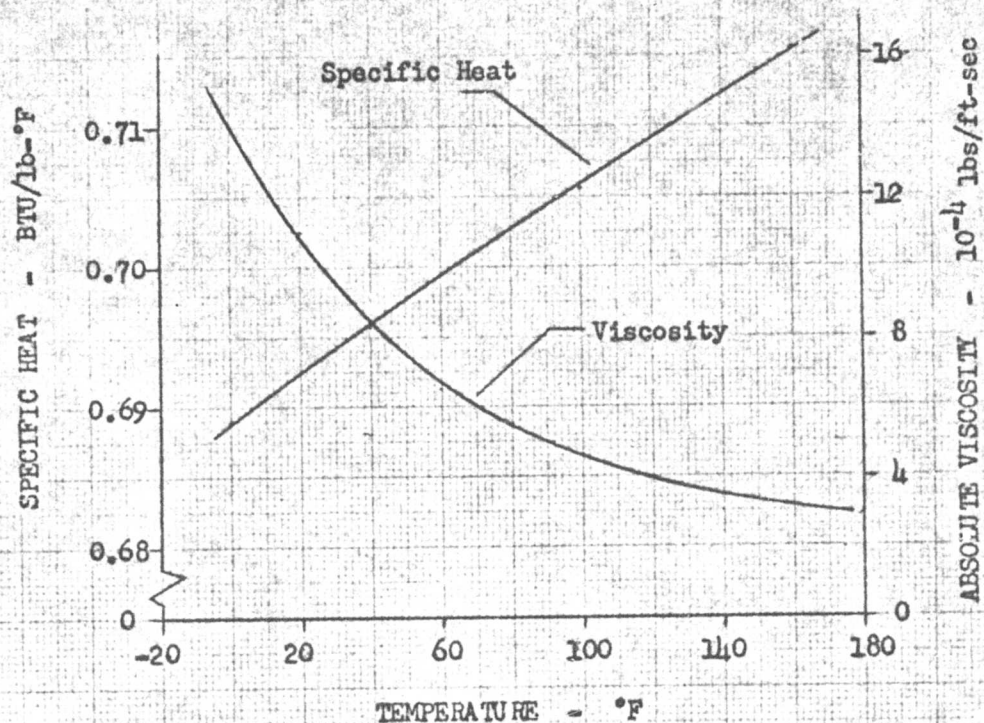
6.4.5 PERFORMANCE OF BI-PROPELLANT ENGINES

Figure 6.4-11 shows the theoretical performance of bi-propellant combinations considered in this section as a function of propellant weight mixture ratio, and referenced to a 100 psia chamber pressure and 50:1 nozzle expansion ratio. Propellant density is sufficiently different for most combinations to affect spacecraft size, so Figure 6.4-12 shows overall propellant bulk density as a function of mixture ratio for these same combinations.

The performance actually delivered by these combinations is reduced from theoretical values by losses attributable to the mixing and combustion process, thermal and cooling conditions, friction drag, variations in propellants and the geometrical influences of the injector, chamber and nozzle. These factors vary with engine design size and operating duty cycle. The latter two factors are the most significant. Fig. 6.4-13 shows performance as a function of thrust for many different bi-propellant engines having different propellants, mixture ratios, chamber pressures and expansion ratios. This performance is actually normalized to a percentage of theoretical vacuum specific impulse (shifting equilibrium) at the engines nominal operating point. The

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| CALC | | | REVISED | DATE | PHYSICAL PROPERTIES MONOMETHYL HYDRAZINE THE BOEING COMPANY | FIGURE 6.4-10 |
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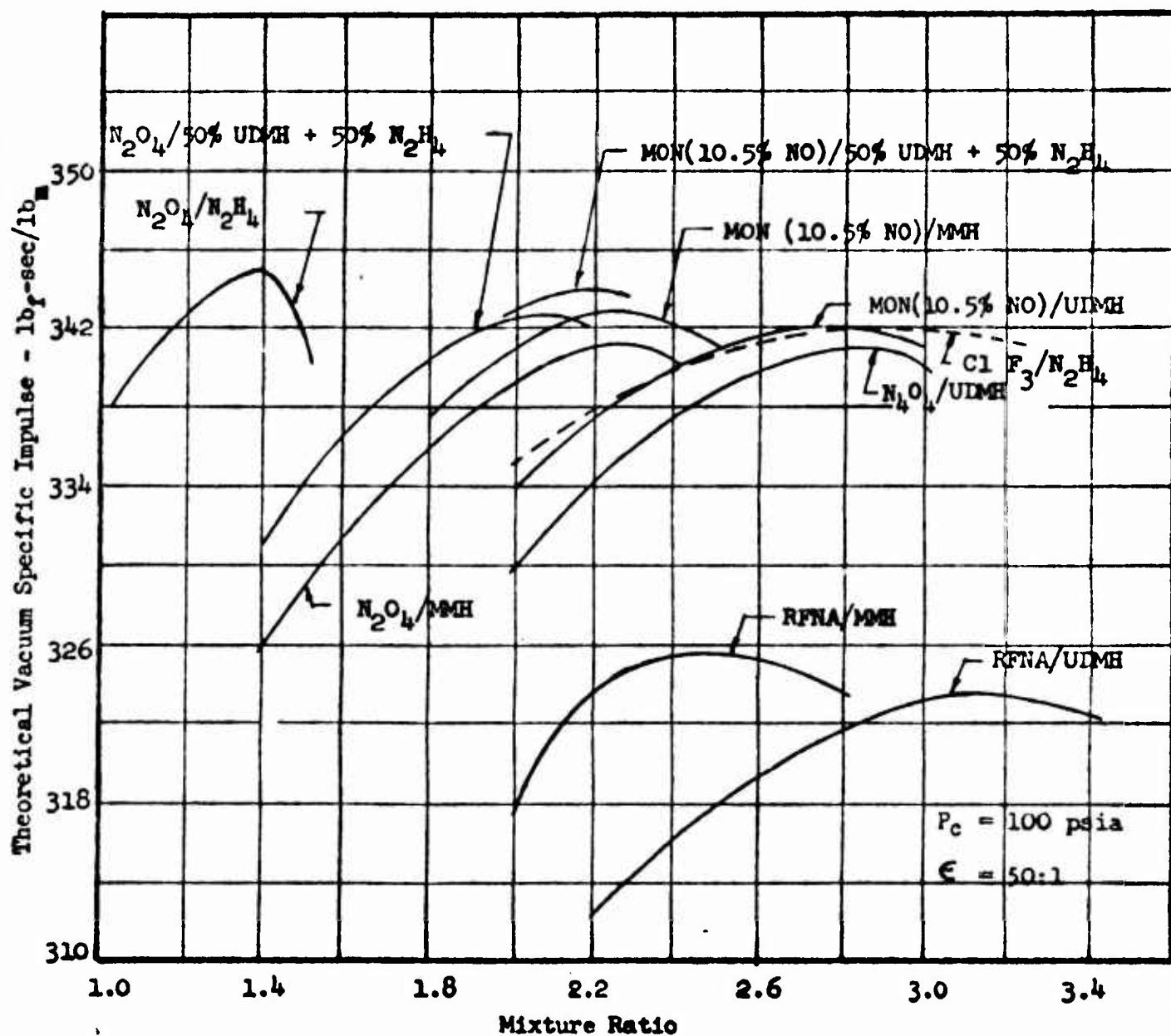


FIGURE 6.4-11 THEORETICAL PERFORMANCE OF BIPROPELLANT COMBINATIONS (Ref. 3)

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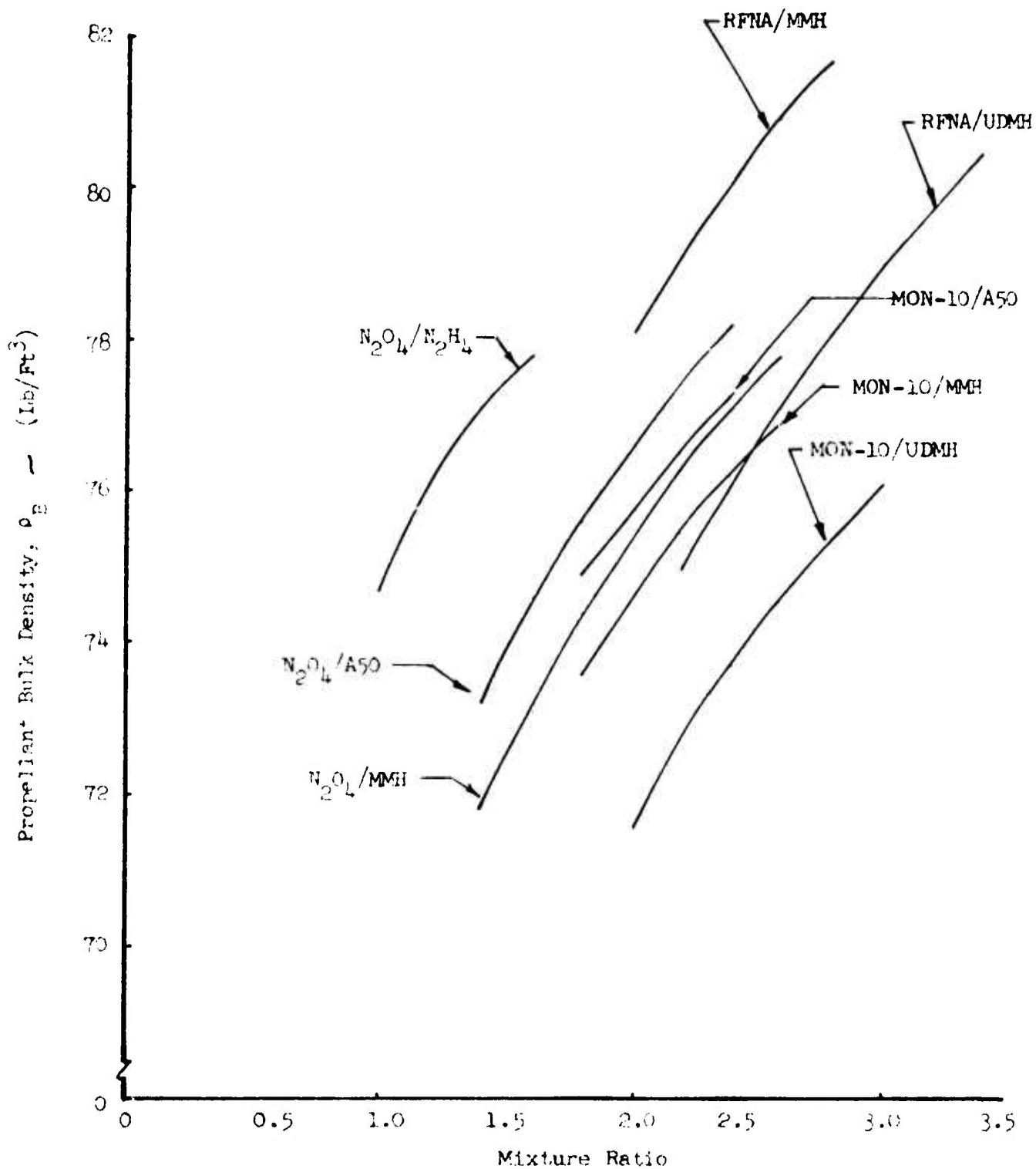
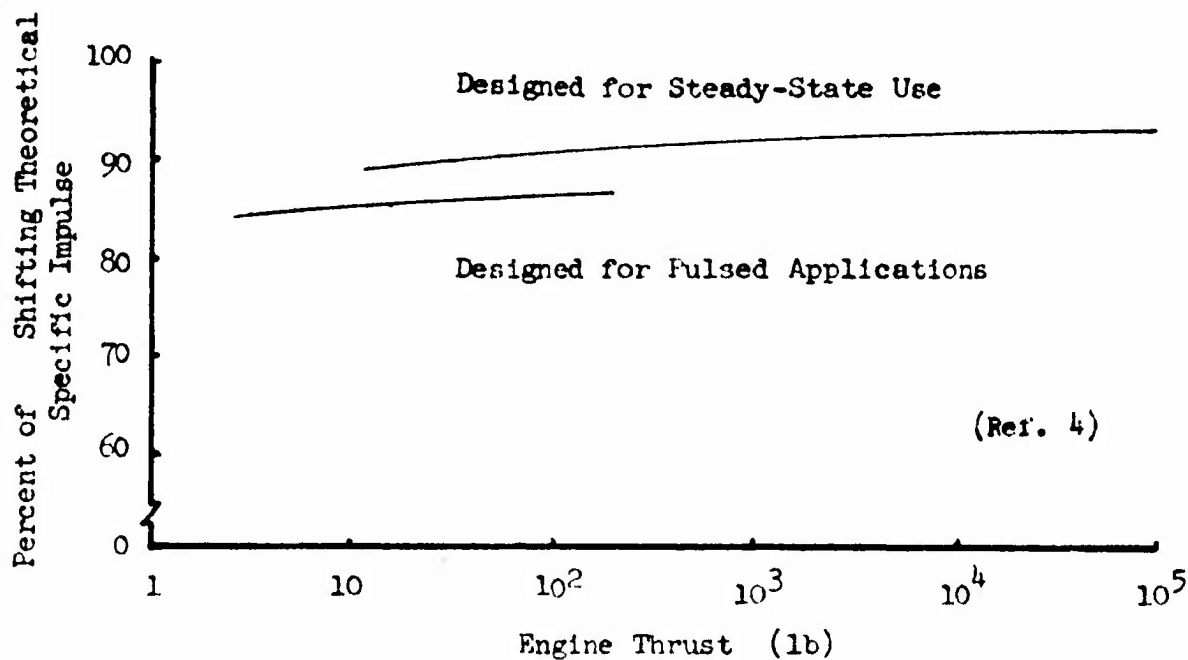
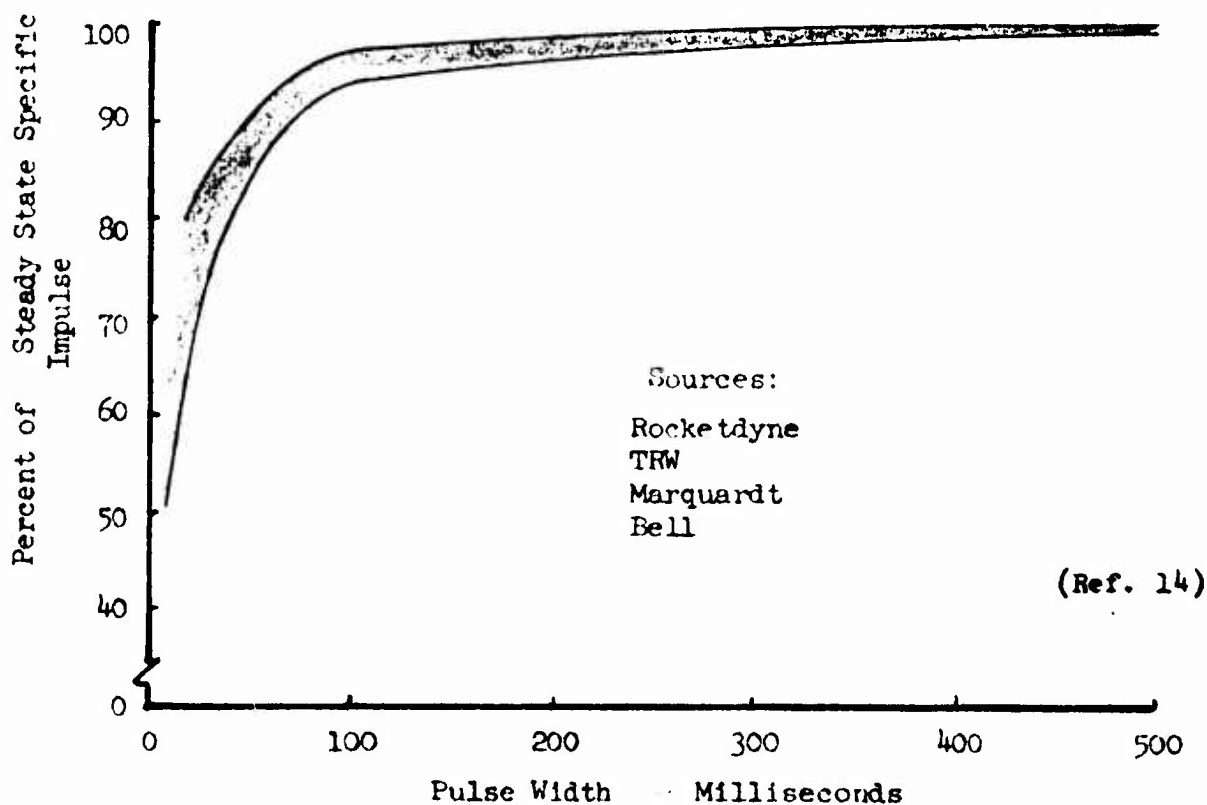


FIGURE 6.4-12 BULK DENSITY OF BI-PROPELLANT COMBINATIONS

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6.4-13 DELIVERED PERFORMANCE OF BIPROPELLANT ENGINES



6.4-14 PERFORMANCE OF RADIATION COOLED PULSE ROCKET ENGINES

discontinuity observed in these data can be attributed to whether the engine was designed for primarily steady state, or pulsing operation.

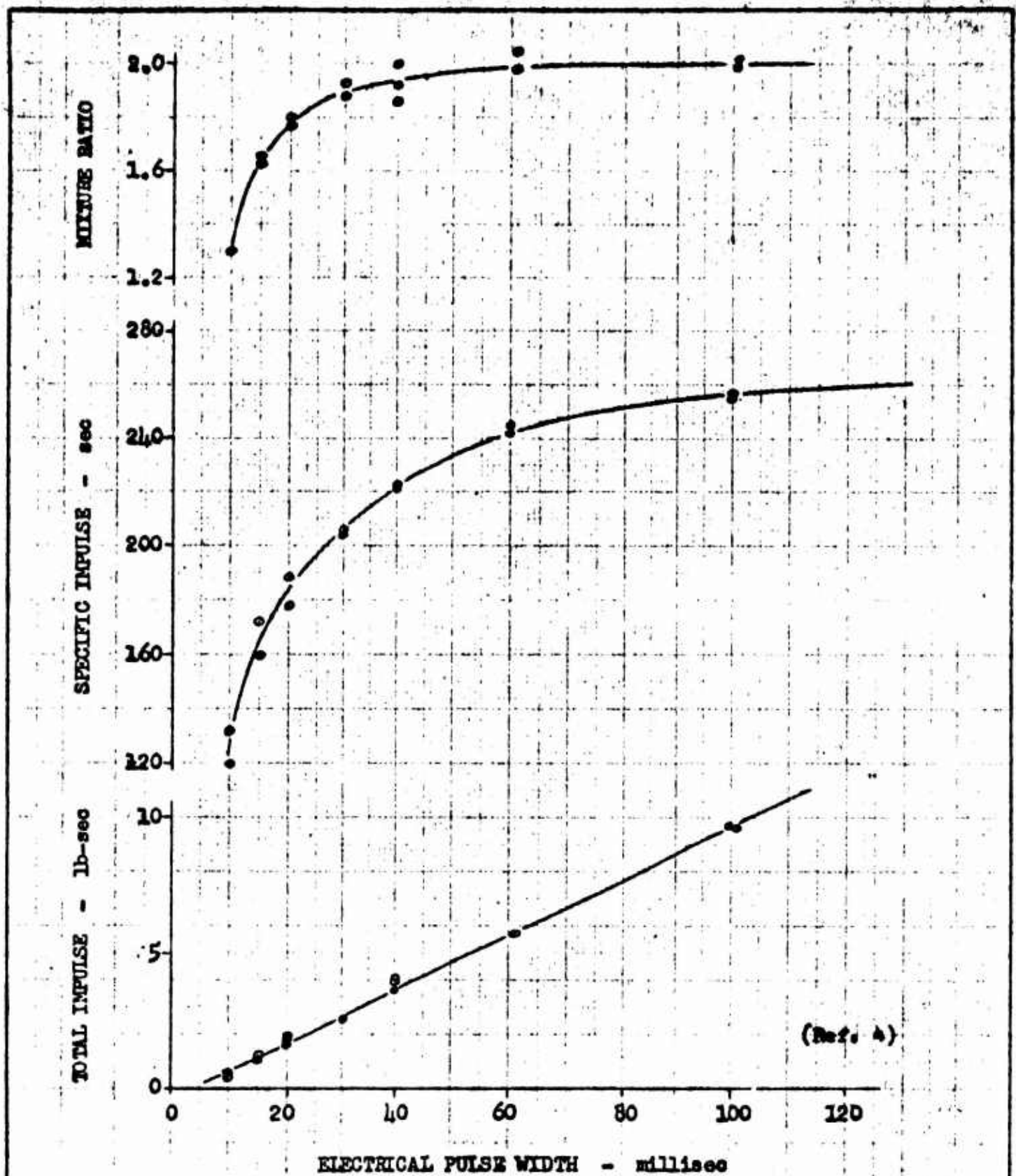
As operating duration is decreased, the relatively constant thrust build-up and decay transients represent a greater portion of the delivered impulse. Transient operation is less efficient since operating characteristics greatly exceed the conditions for which the engine was designed for greater performance, including propellant mixture ratio. This results in decreasing performance as pulse size (i.e., width) decreases. The variations in performance for these conditions is shown in Figure 6.4-14 as a function of delivered steady state performance.

Figure 6.4-15 shows the performance of a typical bipropellant rocket engine using earth storable propellants.

It is sometimes desirable to impart very small impulse bits to perform very small maneuvers. Consequently, the engine capability to provide this control, known as "minimum impulse bit" capability, frequently becomes a very important factor in engine design or selection. The capability for very small impulse bits is determined primarily by how fast the engine valves can be operated. The "hold-up volume," or line volume between the valves and the injector is also important. Engines designed with this capability and good pulsing performance in mind are termed "close-coupled, fast response" engines. As a gross rule, minimum impulse bit capability for these close coupled, fast response engines can generally be estimated by:

$$I_{T\text{Min}} = .01 + .004 F \quad (6.4-1)$$

Minimum impulse bit tolerance generally will not exceed $\pm 10\%$ of $I_{T\text{Min}}$.



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6.4.6 BIPROPELLANT THRUSTOR DESIGN

Bipropellant engines can be configured for spacecraft preliminary design exercises by using the following generalized procedure:

- 1) Assume engine thrust level, F , and duty cycle. These are established for velocity control engines by evaluating limits to maneuver duration, acceleration, gravitational environment, control authority, engine location and duty cycle. Maximum thrust levels are set by acceleration limits for structural or control purposes, single pulse minimum maneuver velocity limits, and engine size and weight. Minimum thrust levels are set by maximum maneuver time limits imposed by engine life, performance penalties associated with finite burn time effects, and thermal, power and communication limits associated with being in the maneuver position.

Thrust level limits for reaction control are evaluated from disturbance torques, minimum impulse bit, response rate, and engine location for limit cycle operation and for all attitude positioning maneuvers.

- 2) Assume thrust chamber pressure, P_c , consistent with the following values representative of current practice:

- a) P_c (radiation cooled engines) = 50 to 100 psia

Current radiation cooled bipropellant engines in the 0.2 to 200 lbs thrust range are evenly distributed throughout this chamber pressure range.

- b) P_c (ablative type engines) = 100 to 150 psia

Current ablative bipropellant engines in the 5 to 150 pound thrust range are rather evenly distributed between 80 to 150 psi chamber pressure.

- c) P_c (regeneratively cooled engines) = 100 to 300 psia

The few regeneratively cooled bipropellant engines designed fit in the

20 to 200 lb thrust range and are generally throttling engines.

Chamber pressures vary, consistent with thrust, with approximately 15 to 150 psia.

- 3) Assume nozzle expansion ratio, ϵ . A good starting point is $\epsilon = 40$ at which the majority of small bipropellant engines are designed.
- 4) Determine propellant specific impulse, I_{sp} for steady state operation from Figures 6.4-11 thru 6.4-15.
- 5) Determine propellant flow rate from:

$$\dot{w} = F/I_{sp} \quad (6.4-2)$$

6.4.7 BIPROPELLANT ENGINE GEOMETRY

Dimensions of bipropellant engines will vary somewhat depending on the basic cooling technique, amount of insulation, and location of engine valves. In preliminary design exercises, the thrust chamber and nozzle major diameter are usually the nozzle exit diameter, d_e , which can be estimated by:

$$d_e = K_e + 0.84 \left[\frac{F\epsilon}{P_c} \right]^{\frac{1}{2}} \quad (6.4-3)$$

where: K_e = a constant relating nozzle exterior to interior dimensions in the exit plane, and having a value of :

$$\begin{aligned} K_e &= 0.3(\text{radiation and regeneratively cooled engines}) \\ &= 1.0(\text{ablative engines}) \end{aligned}$$

Some latitude is available in setting the major engine assembly diameter, d_T , which is frequently affected by such items as engine mounts and propellant values. However, current practice essentially follows:

$$d_T = d_e + K_d \quad (6.4-4)$$

where K_d = a constant relating major assembly diameter to nozzle exit diameter, and having a value of:

$$K_d = 2.9 \text{ (radiation and regeneratively cooled engines)} \\ = 2.2 \text{ (ablative engines)}$$

Total length of a typical bipropellant engine assembly, L_T , including propellant valves can be estimated in preliminary design exercises with:

$$L_T = 3 + \left[\frac{F}{25.5} \right]^{1/2} \left[\epsilon \right]^{1/2} - 1 \quad (6.4.5)$$

6.4.8 BIPROPELLANT ENGINE WEIGHT

Bipropellant engine weight is affected by the cooling techniques used. Engine vendors have conducted numerous parametric studies to relate, for each cooling method, engine weight to thrust, chamber pressure, expansion ratio, and operating duration. Such studies attempt to show weight relationships and, frequently, to indicate specific regions of preference. Experience has shown, however, that they frequently do not correlate well with actual engine designs. This can happen because (1) some factors are really not amenable to parametric treatment, (2) some parameters can be valued differently depending on cooling concept, (3) cooling concept can affect the weight of non-propulsive spacecraft equipment, and (4) there is a degree of optimism which accompanies studies not immediately related to hardware. Vendor differences in cooling concept, design, construction and materials are difficult to relate parametrically. Standard material gages and component sizes actually introduce step functions into weight comparisons. There are also installation and mission related weight factors pertaining to environment, engine mounting, and duty cycle which may obviate direct comparisons. To include these effects, the following

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weight expressions have been derived from the weight and design characteristics of more than 40 different bipropellant rocket engines between 0.2 and 200 pounds thrust, and using earth storable propellants.

a) Full Ablative Engines - The weight of a full ablativ engine, W_a , that is, an engine having an ablativ thrust chamber, an ablativ nozzle assembly, propellant valves, injector, inlet plumbing, fittings, wiring, cabling, and engine mounts, can be roughly estimated from the following expression:

$$W_a = 2.5 + .05 F \quad (6.4-6)$$

where: F = engine thrust level between 5 and 100 lbs and the nozzle expansion ratio is about 40.

This expression does not resolve engine weight variations as a function of operating duration.

b) Radiation Cooled Engines - The weight of a radiation cooled bipropellant engine, W_R , including valves, injector, inlet plumbing, fittings, wiring, cabling, and engine mounts can be estimated from the following expression:

$$W_R = 0.161 \quad 5 + F^{0.4} + \frac{F^{0.85} (\epsilon + 10)}{P_c} \quad (6.4-7)$$

c) Regeneratively Cooled Engines - No mathematical model can be given for small, regeneratively cooled, bipropellant rocket engines since too few such engines exist upon which the analysis could be based.

6.4.9 DEVELOPED BIPOPELLANT THRUSTORS

Table 6.4.3 lists bipropellant engines developed for spacecraft applications and for research purposes.

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TABLE 6-4-3 DEVELOPED BIPROPELLANT THRUSTORS

| THRUST (LBS) | PROGRAM, CONTRACT OR AGENCY | VENDOR | MODEL | TYPE CHAMBER/ NOZZLE | PROPELLANT OX FUEL | MIXTURE RATIO (O/F) | P _c (PSIA) | P _{in} (PSIA) | ε | DIMENSIONS—INCHES | | | WEIGHT (LBS) W/O VALVE | T ₁ MIN | POWER (WATTS) | MAX LIFE (SECS) |
|-----------------|-----------------------------------|--------|--------------|----------------------------|--|---------------------------|--------------------------|---------------------------|------|--------------------|---------------------|--------------------|---------------------------|-----------------------|------------------|-----------------------|
| | | | | | | | | | | W/O VALVE WIDTH | W/O VALVE LENGTH | W/O VALVE WIDTH | | | | |
| 0.5 | IR&D | BELL | | RADIATION | O ₂ CH ₄ | | 360 | 42 | 50 | 1.0 | 2.6 | 5.6 | 0.20 | | | |
| 1.0 | IR&D | BELL | 8599 | RADIATION | N ₂ O ₄ /ASO | | 255 | 50 | 60 | | | 5.95 | 0.29 | | 15 | 30 |
| 1.0 | NAS-5458 | BELL | 8360 | RADIATION | N ₂ O ₄ /ASO | 1.4 | 255 | 50 | 60 | 2.73 | 4.8 | 2.73 | 0.52 | 1.10 | 20 | 3400 |
| 5.0 | IR&D | BELL | 8348T | RADIATION | N ₂ O ₄ /ASO,MMH | 1.6 | 275 | 60 | 40 | 2.63 | 5.8 | 2.63 | 1.07 | 1.65 | 20 | 3400 |
| 5.0 | IR&D | BELL | 8348C | RADIATION | N ₂ O ₄ /ASO,MMH | 1.6 | 275 | 60 | 40 | 2.63 | 5.8 | 2.63 | 0.72 | 1.30 | 20 | 3400 |
| 5.0 | ADV SYN- COMP | MARQ. | MA-124 | RADIATION | N ₂ O ₄ /MMH,MHF | 1.6 | 283 | 96 | 170 | 2.2 | 4.4 | 3.95 | 1.5 | 0.29 | 35 | 9000 |
| 5.0 | IR&D | MARQ. | R-9A | ABLATIVE | N ₂ O ₄ /MMH,MHF | 1.6 | 280 | 135 | 40 | 2.8 | 5.0 | 3.6 | 3.2 | 0.028 | | 500 |
| 5.0 | | UTC | | ABLATIVE | N ₂ O ₄ /MMH | 1.6 | | | | | | | | | | |
| 16 | AGENA, GEMINI | BELL | 8101 8250 | RADIATION | MONODIMH | 1.1 | 252 | 81 | 55.6 | | 7.3 | | 2.2 | | | 2650 |
| 16 | | BELL | 8500 | RADIATION | N ₂ O ₄ /ASO | 1.0 | 276 | 81 | 55.6 | 4.2 | 6.55 | 4.2 | 10.8 | 2.7 | 20 | 3400+ |
| 20 | IR&D | MARQ. | R-7B | ABLATIVE | N ₂ O ₄ /MMH,MHF | 1.6 | 282 | 130 | 40 | 2.8 | 6.8 | 4.8 | 7.9 | 3.9 | 0.10 | 35 |
| 20 | IR&D | UTC | | ABLATIVE | N ₂ O ₄ /MMH | | | | | | | | | | | |
| 20 | NAS-B- 20795 | AGC | | | | | | | | | | | | | | |
| 22 | IR&D | BELL | | ABLATIVE | N ₂ O ₄ /UDMH | 1.0 | 290 | 40 | 5.1 | | | | 2.4 | | | |
| 22 | IR&D | BELL | 8999-T | RADIATION | N ₂ O ₄ /ASO,MMH | 1.3 | 290 | 40 | 50 | 4.0 | 7.5 | 4.0 | 10.38 | 3.2 | | |
| 22 | IR&D | BELL | 8999-C | RADIATION | N ₂ O ₄ /ASO,MMH | 1.3 | 290 | 40 | 50 | 4.0 | 7.5 | 4.0 | 10.38 | 1.8 | | |
| 22 | MOL | MARQ. | R-E | RADIATION | N ₂ O ₄ /MMH,MHF | 1.6 | 276 | 93 | 40 | 3.5 | 6.1 | 6.0 | 10.1 | 2.88 | 0.002 | 35 |
| 23.5 | GEMINI | RD | SE-6 | ABLATIVE | N ₂ O ₄ /MMH | | | | | | | | | | | 35,200 |
| 25.0 | GEMINI | RD | SE-7 | ABLATIVE | N ₂ O ₄ /MMH | | | | | | | | | | | |
| 25.0 | TRANSJAGE | RD | SE-9 | ABLATIVE | N ₂ O ₄ /MMH | | | | | | | | | | | |
| 25.0 | GEMINI | TRW | | | N ₂ O ₄ /MMH | 1.3 | 295 | 150 | 295 | 4.8 | 4.8 | 4.8 | 7.2 | 6.75 | 0.025 | 26.7 |
| 25 | IR&D | TRW | URSAZER | RADIATION | N ₂ O ₄ /MMH | 1.6 | 292 | 90 | 105 | | | 3.7 | 11.2 | 4.2 | 0.20 | 70 |
| 25 | IR&D | BELL | 8441 | RADIATION | N ₂ O ₄ /ASO | 1.6 | 290 | 80 | 40 | 3.62 | 7.2 | 3.62 | 10.5 | 2.1 | 2.9 | 28 |
| 45 | TRANSJAGE | RD | SE-9 | ABLATIVE | N ₂ O ₄ /ASO | | | | | | | | | | | 3400 |
| 48 | AGENA | RD | SE-5 | ABLATIVE | N ₂ O ₄ /MMH,MHF | 1.42 | 272 | 150 | 280 | 4.5 | | 4.5 | 14.0 | | | 600 |
| 72 | S-IVB ULLAGE | RD | SE-7 | ABLATIVE | N ₂ O ₄ /MMH | 1.72 | 274 | 102 | 40 | | | | | | | |

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TABLE 4-3 DEVELOPED 81 PROPELLANT THRUSTERS (Cont'd)

| THRUST LBS. | PROGRAM CONTRACT OR AGENCY | VENDOR | MODEL | TYPE CHAMBER/ NOZZLE | PROPELLANT O/F FUEL | MIXTURE RATIO (W/F) | P _c (PSIA) | P _e (PSIA) | C _d (SEC) | E | DIMENSIONS - INCHES | | | | WEIGHT (LBS.) W/O VALVE | WITH VALVE | I _{sp} MIN | POWER LIFE (HOURS) | MAX LIFE (HOURS) |
|----------------|----------------------------------|--------|----------------|----------------------------|---|---------------------------|--------------------------|--------------------------|-------------------------|------|---------------------|-----------|-----------|-----------|----------------------------|---------------|------------------------|--------------------------|------------------------|
| | | | | | | | | | | | W/D VALVE | W/D VALVE | W/D VALVE | W/D VALVE | | | | | |
| 75 | AF-40-401 -47-40095 | AGC | | | | | | | | | | | | | | | | | |
| 85 | GEMINI | RD | SE-7 | RADIATION | N ₂ O ₄ /MMH | | | | | | | | | | | | | | |
| 95 | IRAD | TRW | APOLLO 93 | RADIATION | N ₂ O ₄ /MMH | 2.0 | 200 | 150 | 295 | 91 | 4.8 | 4.8 | 4.8 | 7.2 | | 6.75 | 0.25 | 28.7 | 100 |
| 100 | UNIV. ENG. NAS-7-305 | BELL | 8374 | RADIATION HEAT SINK | N ₂ O ₄ /MMH | 1.6 | 290 | 80 | 175 | 40 | 8.35 | 14.0 | 8.35 | 19.0 | | 6.82 | 0.5 | | 3600 |
| 100 | NASA-4MSD NAS-9-1522 | BELL | 8290 | RADIATION | N ₂ O ₄ /ASO | 2.0 | 290 | 80 | | 40 | 5.9 | 13.7 | 5.9 | 14.7 | 5.6 | 6.8 | | 28 | 9 |
| 100 | IRAD | BELL | 8999-C | RADIATION | N ₂ O ₄ /ASO | 1.6 | 290 | 80 | | 40 | 4.0 | 8.8 | 4.0 | 14.54 | 3.5 | 4.7 | | 30 | |
| 100 | IRAD | BELL | 8999-T | RADIATION | N ₂ O ₄ /ASO | 1.6 | 290 | 80 | | 40 | 4.0 | 8.8 | 4.0 | 16.56 | 5.3 | 6.5 | | 30 | |
| 100 20 | MISC-LTV | BELL | 8814 | RADIATION | N ₂ O ₄ /ASO | 1.6 | 295 | 85-90 | 200 | 40 | 7.4 | 14.25 | | | | | | | 15 |
| 100 | APOLLO LO MOL | MAPO | MA-109 R-40 | RADIATION | N ₂ O ₄ /ASO | 2.0 | 276 | 96 | 170 | 40 | 5.74 | 11.26 | 6.0 | 13.42 | 3.04 | 4.9 | 0.1 | 26 | 1200 |
| 100 | ORIGINAL MAPO APOLLO | MAPO | R-40 | RADIATION | N ₂ O ₄ /MMH, MMH | 1.6 | 307 | 96 | | 40 | 5.74 | 11.26 | 6.0 | 13.42 | 3.04 | 4.9 | | 26 | 5000 |
| 100 | IRAD | MAPO | R-30 | ABLATIVE | N ₂ O ₄ /MMH, MMH | 1.6 | 286 | 126 | 280 | 40 | 5.4 | 10.5 | 5.7 | 13.5 | | 9.5 | 0.48 | 26 | 300 |
| 100 87 | IRAD | TRW | URSA ROR | RADIATION | N ₂ O ₄ /MMH | 1.6 | 295 | 90 | 185 | 52 | | | 5.9 | 13.6 | | 4.7 | 0.4 | 50 | 100 |
| 100 | NAS-8-20095 AGC | | | | | | | | | | | | | | | | | | |
| 100 | GEMINI | RD | SE-7 | RADIATION | N ₂ O ₄ /MMH | | | | | | | | | | | | | | |
| 100 | IRAD | UTC | | RADIATION | N ₂ O ₄ /MMH | | | | | | | | | | | | | | |
| 100 | UNIV. ENG. C-1 | THOKOL | TD-345 | ABL + REGEN | N ₂ O ₄ /MMH | 1.6 | | | | | | | | | | | | | |
| 100-30 | SURVEYOR | THOKOL | | REGEN + RAD | MMH/MMH H ₂ O | | | | | | | | | | | | | | |
| 100-80 | SCOUT 101 MISSILE | RD | P-4 | REGENERATIVE | IRFNA/ HYDYNE | | | | | | | | | | | | | | |
| 150 | LUNAR HOPPER | TRW | | | | | 85-112 | 40 | | | | | 5.82 | | 3.80 | | | | 22 |
| 150-30 | SURVEYOR BACK-UP | TRW | | ABLATIVE | MMH/MMH | 1.5 | 291 | 110-22 | 320 | 32.2 | 5.75 | | 5.75 | 13.3 | | 8.3 | | 34 | 17 |
| 150-20 | SURVEYOR BACK-UP | TRW | MIRA 180 | ABL + REG | N ₂ O ₄ /MMH | 1.6 | 295 | 150-16 | | 38.2 | | | | 8.5 | | | | 285 | 20 |
| 200 | AGENA/ GEMINI | BELL | 8801 8250 | HEAT SINK | MMH/MMH | 1.15 | 254 | 96 | | 15.6 | 6.0 | 11.0 | | 15.54 | 9.9 | 10.4 | | 600 | 35 |
| 200 | IRAD | TRW | URSA 700 | RADIATION | N ₂ O ₄ /MMH | 1.6 | 295 | 90 | 185 | 40 | | | 8.0 | 18.4 | | 8.0 | 1.0 | 50 | 100 |

(Refs. 14, 20, 29, 30)

7.0 SYSTEMS CONSIDERATIONS

Certain systems considerations are important in a discussion of velocity control and reaction control thrusters. The thruster itself is actually a small weight and geometry penalty to the system. But thruster design significantly affects propulsion system characteristics which, in turn, are usually important to the spacecraft. Spacecraft design is especially sensitive to power requirements, command and control procedures, data provisions, thrust vector and thermal control requirements, propellant performance, and propellant storage pressures. These factors will be briefly discussed.

7.1 INTERFACES

The thruster itself interfaces with the propulsion system directly and the spacecraft. The propulsion system also interfaces directly with the spacecraft. Both the thruster and the propulsion system have an interface with the mission as it relates to trajectory duration and sequencing. Primary interfaces are shown in Table 7.1-1, and discussed below:

- a) Propellant Feed System -- The thruster assembly connects directly to the propellant feed system at the inlet side of the engine or engine valves. This connection directs propellants from the feed system to the engine injector. It is affected by propellant flow rate and by propellant supply pressure. Engine chamber pressure is related to feed system pressure drops and propellant supply pressures in the tanks. Hence, engine chamber pressure affects system weight to a large extent since propellant tanks, and frequently, plumbing lines, are designed as pressure vessels.

The engine to feed system interface also may include torsional and translational loads imparted to feed system plumbing through engine gimbally for

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TABLE 7.1-1 ELECTRICAL, MECHANICAL AND STRUCTURAL INTERFACES

| Type of Interface | Description | Boundary Definition |
|---------------------------------|--|---|
| <u>Propellant Feed System</u> | | |
| Mechanical | Plumbing attachment to valve inlets | Valve inlet |
| Mechanical | Torque, translation on gimballing | Valve inlet |
| <u>Thrust Vector Deflection</u> | | |
| Mechanical | Actuator linkage attachment | Actuator linkage bosses |
| Mechanical | Pivot location | Engine gimbal assembly |
| Thermal | Exhaust plume to jet vane | Exhaust plume temperature profile |
| <u>Structural</u> | | |
| Mechanical | Engine attachment to thrust mount | Attach plane surface, gimbal mount |
| Mechanical | Clearance in all gimballed positions | Engine assembly total envelope in all deflected positions |
| Pneumatic | Exhaust plume to spacecraft impingement | Exhaust plume pressure profile |
| <u>Thermal Control</u> | | |
| Thermal | Heat soak back through thrust mount | Watts at thrust mount attach plane |
| Thermal | Heat transfer through propellant line to valve inlet | Valve inlet heat flux |
| Thermal | Exhaust plume to spacecraft heat transfer | Exhaust plume heat rate profile |
| Thermal | Engine radiation to spacecraft | Engine heat rate profile |
| Thermal | Engine heater assembly | Heater location |
| <u>Electrical</u> | | |
| Electrical | Signal to power, control, sequence engine valves | Electrical input to panel |
| Electrical | Power, readout of engine assembly instrumentation | Electrical input to instrument portion, electrical panel |
| <u>Service</u> | | |
| Electrical | Electrical connections to check wiring continuity, operation of thrust level selector, and valve position indicators | Electrical connection to allow testing |
| Hydraulic | Liquid and gas service provisions to spacecraft | Service coupling |
| Pneumatic | | |

thrust vector control. A deliberate attempt should be made in this regard to distribute these loads in such a manner as to minimize their effect on gimbal actuator control authority.

- b) Thrust Vector Control -- Engines used for velocity control may require some thrust vector control capability. This capability may take the form of gimbaling the engine, deflecting engine exhaust by vanes in the exhaust stream, or differential thrust control of several engines. Engine gimbaling involves a moveable engine assembly which requires a large geometrical envelope for clearance reasons, mechanical connections for driving actuators and a hinge or multi-axis assembly as a pivot. Loads are applied at the actuator attachments, hinge points, and propellant supply plumbing. Jet vane systems involve a fixed engine assembly. Jet vanes are primarily sensitive to thermal loads from the propellant exhaust to the vane limiting it to use with lower temperature systems. In multi-engine assemblies used for velocity control, differential throttling or pulsing can be used for control of the mean effective thrust vector. The primary interfaces in this case are electrical for command and control, and thermal, as related to engine behavior in the particular duty cycle.
- c) Structural Attachments -- The thruster interfaces either with the spacecraft or with propulsion system structure at a specific attach point at which thrust loads are transmitted. This interface may also affect clearance requirements when gimballed. Precise location of the engine on the thrust mount is important, especially in fixed engine installations, to insure that the nominal thrust vector is directed through the spacecraft center of gravity.

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- d) Thermal Control -- Thermally, the thruster affects the spacecraft environment, and is in turn affected by the spacecraft and the space environment. Thruster induced thermal loads arise from radiation and conduction from the engine and radiation from the exhaust plume. Thermal interfaces exist at the engine attach points, propellant plumbing, gimbal attach points, thermal shielding, and the radiation profiles of the engine and exhaust plume.
- e) Electrical -- The electrical interface includes all electrical provisions for power, control and sequencing of fuel and oxidizer valves, and instrumentation and for data readout.
- f) Service -- The service interface includes all electrical provisions for verifying electrical continuity and for all service instrumentation. It also includes hydraulic, mechanical, and pneumatic provisions for pre-flight service and installation.

7.2 SYSTEM POWER

Electrical power is used by the propulsion system to actuate valves on the engine, in the pressurization system, and in the propellant system, to drive actuators for thrust vector control, to process commands and data concerning system operation, and to elevate temperatures locally by electrical heaters.

Figure 7.2-1 shows electrical power requirements for operating many existing stored gas, monopropellant and bipropellant engines. These are total engine valve electrical power requirements for non-redundant installations. Thus, bipropellant engine requirements involve both the oxidizer and fuel valves. These power values should be doubled when redundant valves are involved. It is important to note that these are not minimum power curves, but are regions which show the power requirements associated with actual installations having

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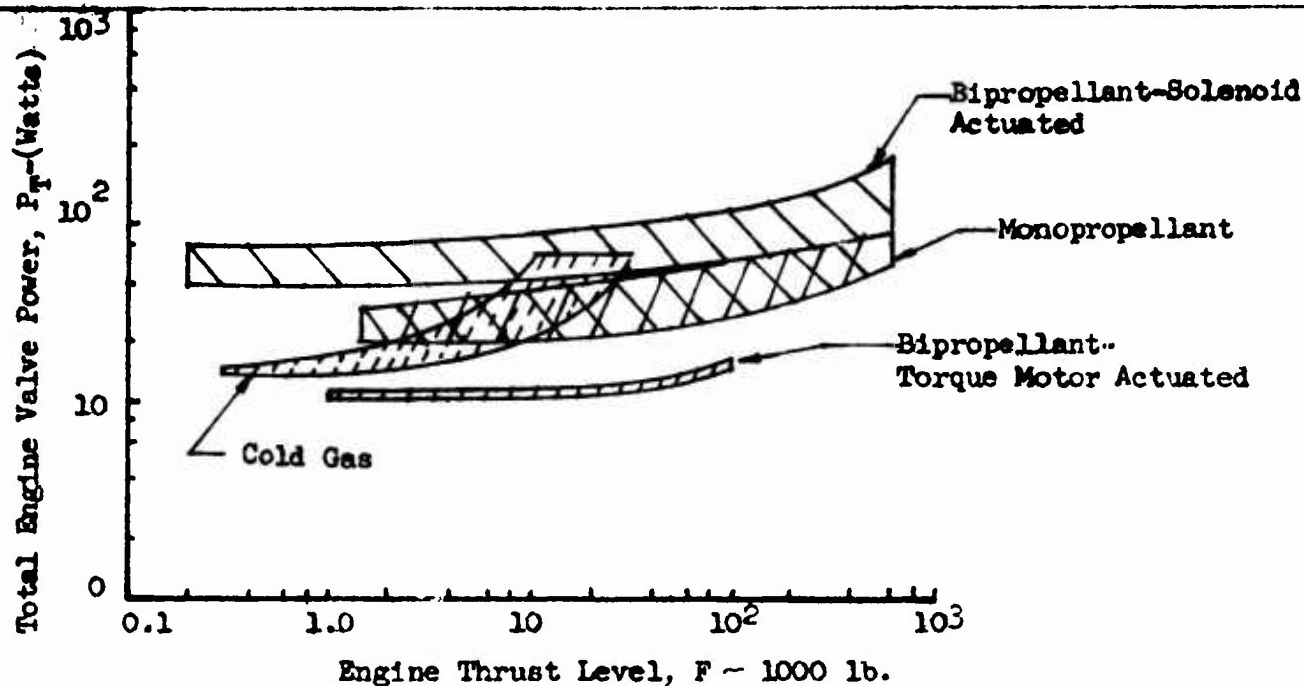


FIGURE 7.2-1 POWER REQUIREMENTS - EXISTING ENGINES VALVES

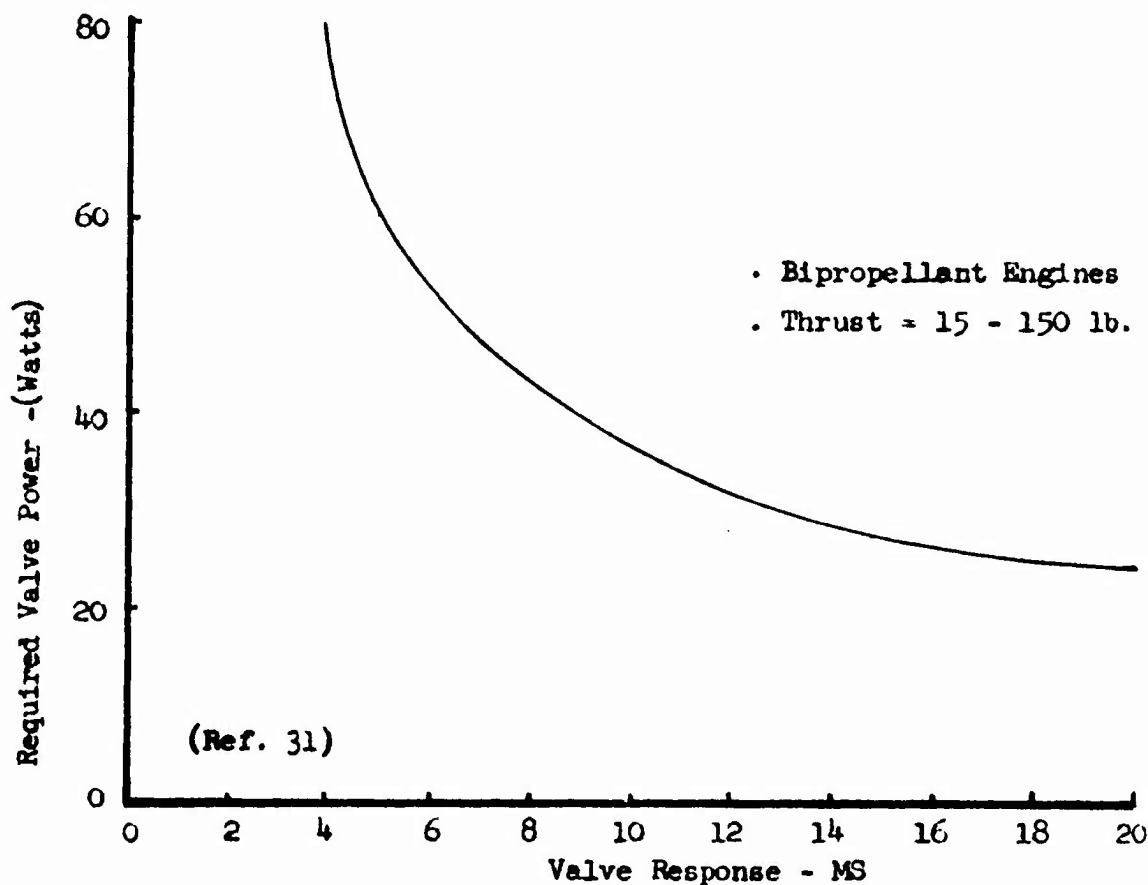


FIGURE 7.2-2 POWER-RESPONSE CHARACTERISTICS OF SOLENOID VALVE

different response conditions. The general flatness of these curves develops from the fact that, in many installations, the same valve is used at different thrust levels and response characteristics. Figure 7.2-2 shows the relationship of valve power to response for a typical solenoid valve.

System power requirements may greatly exceed engine requirements, especially if many valves are used in the pressurization or propellant feed systems.

Power requirements for command, control, and telemetry data concerning propulsion system status are small.

Heated gas thruster systems using electrical heaters may be expected to have significant weight allotments for power. Similarly, electrical heaters used for thermal control may consume large amounts of energy by operating at low power for extended periods or by operating briefly at high power levels such as during periods of occultation.

In summary, propulsion system power requirements develop from the needs of many components, having different power ratings and operating times. It is important in system design to develop a propulsion system power requirements schedule to identify power consuming elements, to sequence power consuming events, and to help integrate propulsion system and spacecraft power requirements.

7.3 THRUST VECTOR CONTROL

Engines used for velocity control purposes need some sort of directional control over the engine thrust vector to position it properly with respect to the spacecraft center-of-gravity. In numerous bipropellant engines this capability is provided by gimbaling the engine in two axes normal to the thrust vector. This procedure requires mounting the engine within a movable assembly of sufficient strength to withstand structural and thrust loads, and to provide actuator attach points of similar capability. Engine inlet plumbing and cabling must also be positioned and designed to minimize their loads on the actuator and to prevent clearance problems.

It is also possible to rigidly fix the engine assembly and direct the effective thrust vector by gimbaling the nozzle, or by moving vanes positioned in the exhaust stream at the nozzle exit. Vanes are conveniently used with monopropellant engines since the engine exhaust is free of solid particles and at a low enough temperature to allow simple stainless steel vanes.

Other possible vector control methods include translating the engine or engine components, injecting fluids non-uniformly into the exhaust stream (secondary injection) and by using auxiliary jets. Of all these methods, only the latter has been used in liquid propulsion systems for small spacecraft. Surveyor uses this method by differentially throttling three vernier engines one of which can gimbal in a single axis.

Figure 7.3-1 shows weight estimates of rocket engine thrust vector control systems which are sufficient for preliminary design purposes. The gimbal system consists of a gimbal platform, movable in two axes, which is firmly attached to the engine and to the spacecraft, plus the necessary actuators, wiring and cabling. Alignment adjustments with respect to the spacecraft are commonly provided at the gimbal mount-to-spacecraft mating face. Jet vane assemblies, used in monopropellant engines, consist of four jet vanes, four rotary actuators, a mounting ring, and the necessary wiring and cabling.

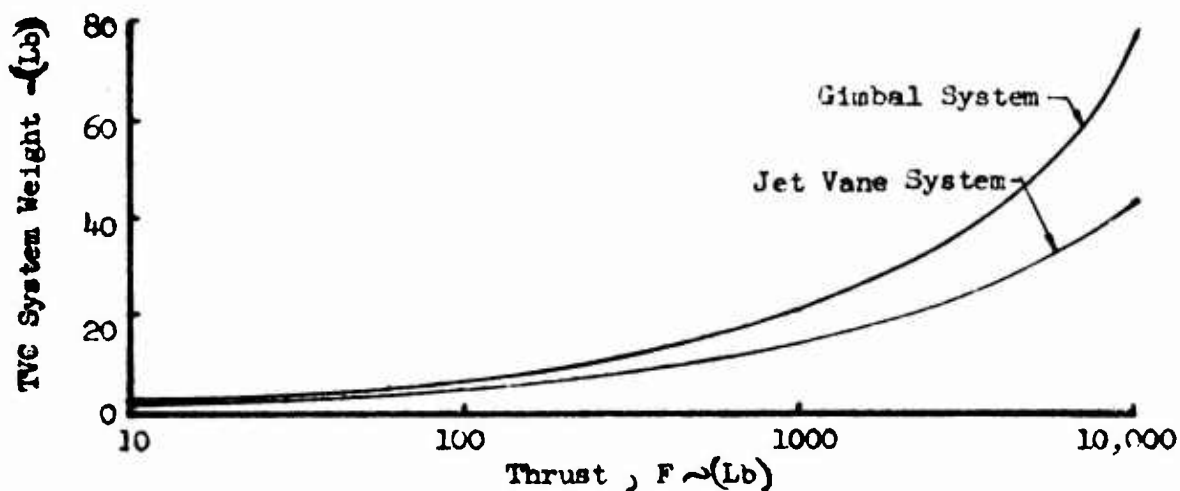


FIGURE 7.3-1 THRUST VECTOR CONTROL SYSTEM WEIGHT

Figure 7.3-2 relates jet vane deflection to effective gimbal angle and specific impulse penalty. Figure 7.3-3 relates jet vane torque motor actuator performance power requirements.

7.4 THERMAL CONTROL

Thermal control of the spacecraft is concerned with, among other things, providing a proper thermal environment to the propulsion system and accommodating the thermal loads which it imposes.

Propellant temperature affects engine performance as it relates to response, impulse bit size, bipropellant mixture ratio, and sometimes, specified impulse. These factors can be resolved at a given temperature. Spacecraft are, however, designed to operate over a range of conditions, hence some variation can be expected in the performance parameters. Absolute limits may also exist such as the 35°F freezing limit of hydrazine under normal conditions. Thermal control provisions, such as heaters, are incorporated to maintain propulsion system operation within specified performance limits.

The engine will absorb or dissipate thermal energy during non-operating periods depending on its orientation with respect to the sun and the character of thermal paths from the spacecraft. Radiation cooled engines are most strongly affected since they are radiators. Proper thermal insulation at engine mounting points is a necessity. The injector in all rocket engines views space through the nozzle throat and can, consequently, exceed its thermal margins unless adequate provisions are made.

The engine and exhaust plume are large radiative heat sources during operation, especially in the radiation cooled engines. Figure 7.4-1 shows the exterior thermal profile of typical rocket engines during steady state operation.

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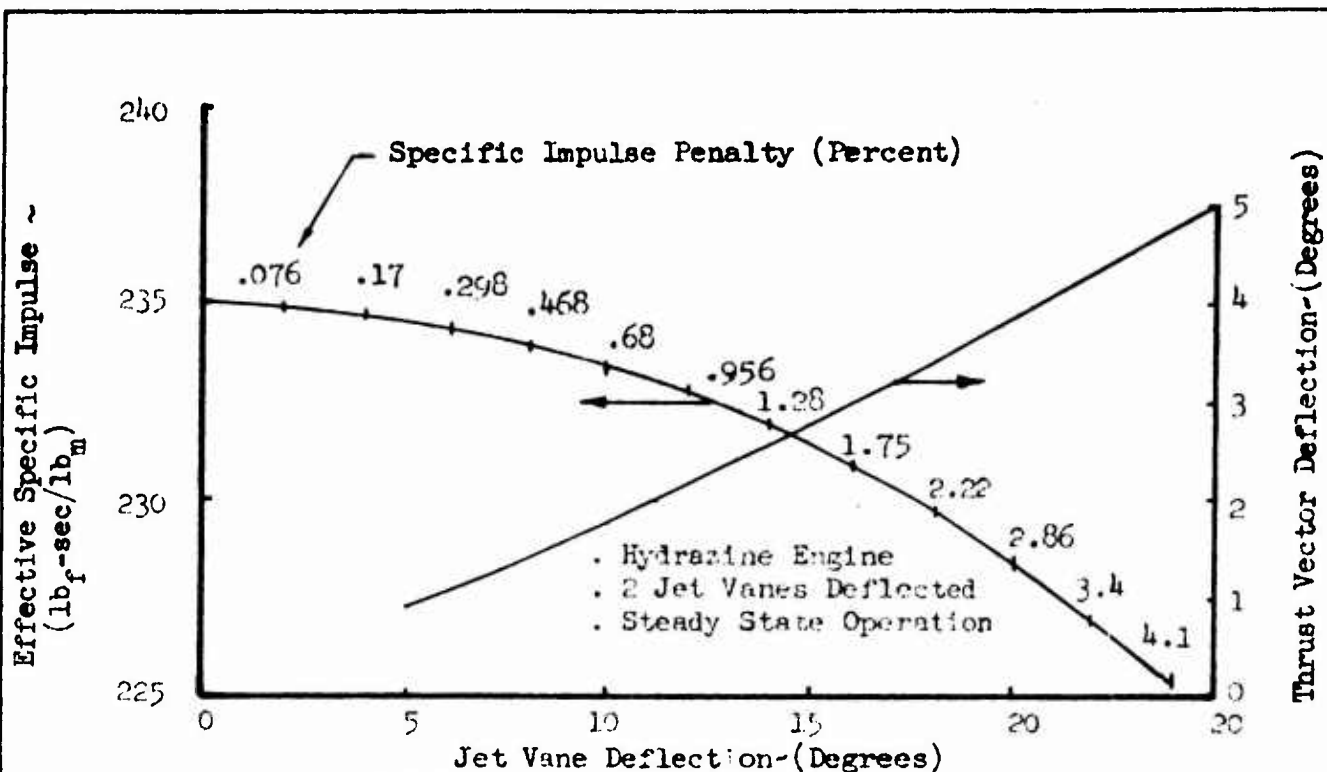


FIGURE 7.3-2 TYPICAL JET VANE TVC PERFORMANCE

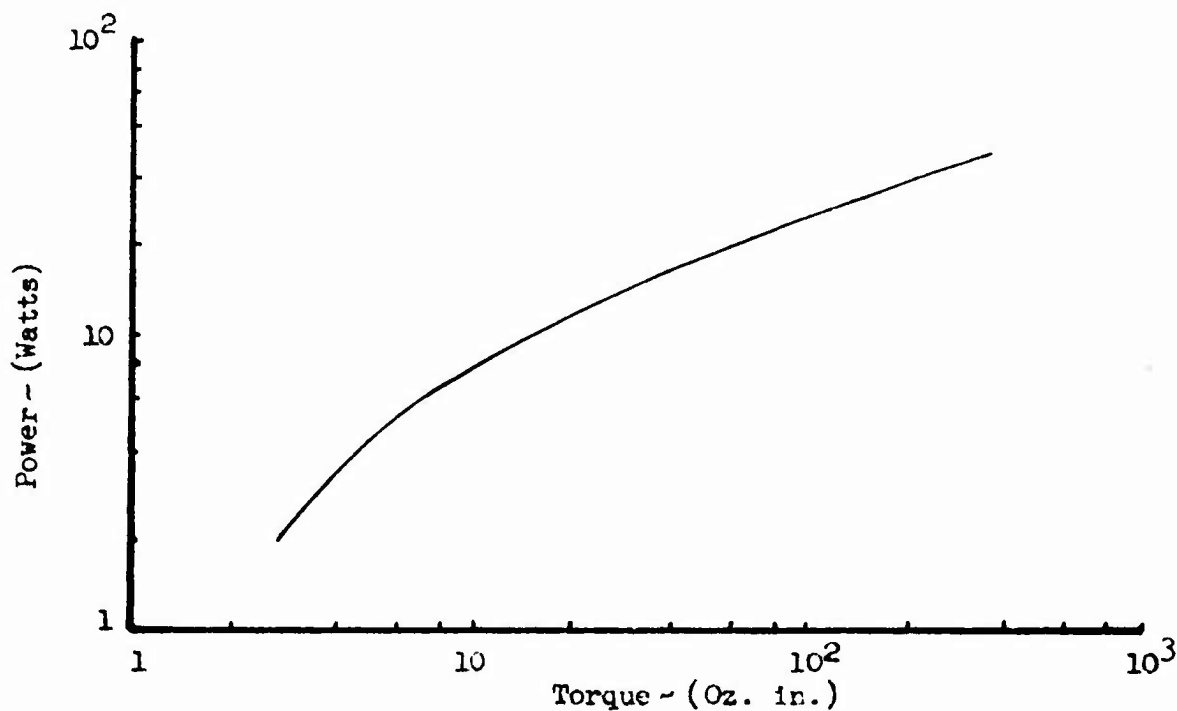


FIGURE 7.3-3 TYPICAL JET VANE ACTUATOR POWER REQUIREMENTS

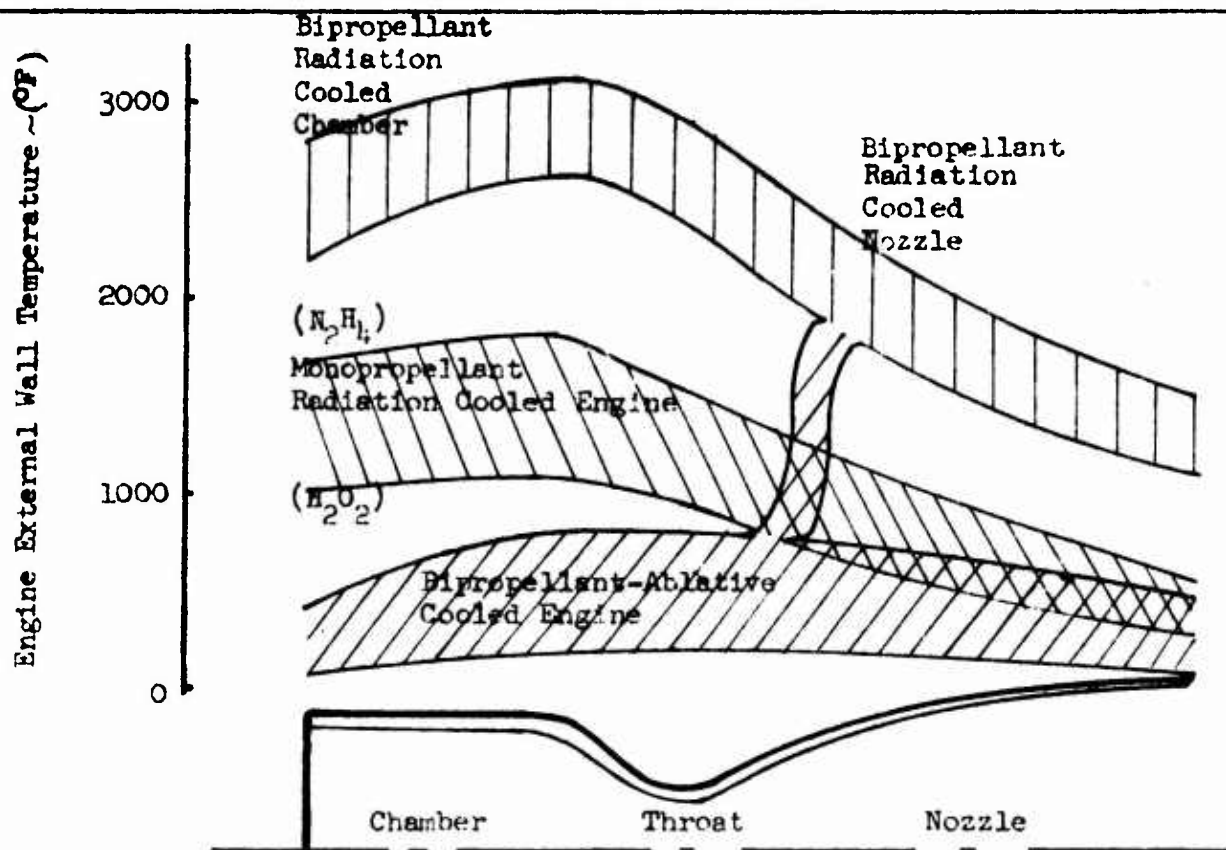


FIGURE 7.4-1 ENGINE EXTERNAL TEMPERATURE PROFILES

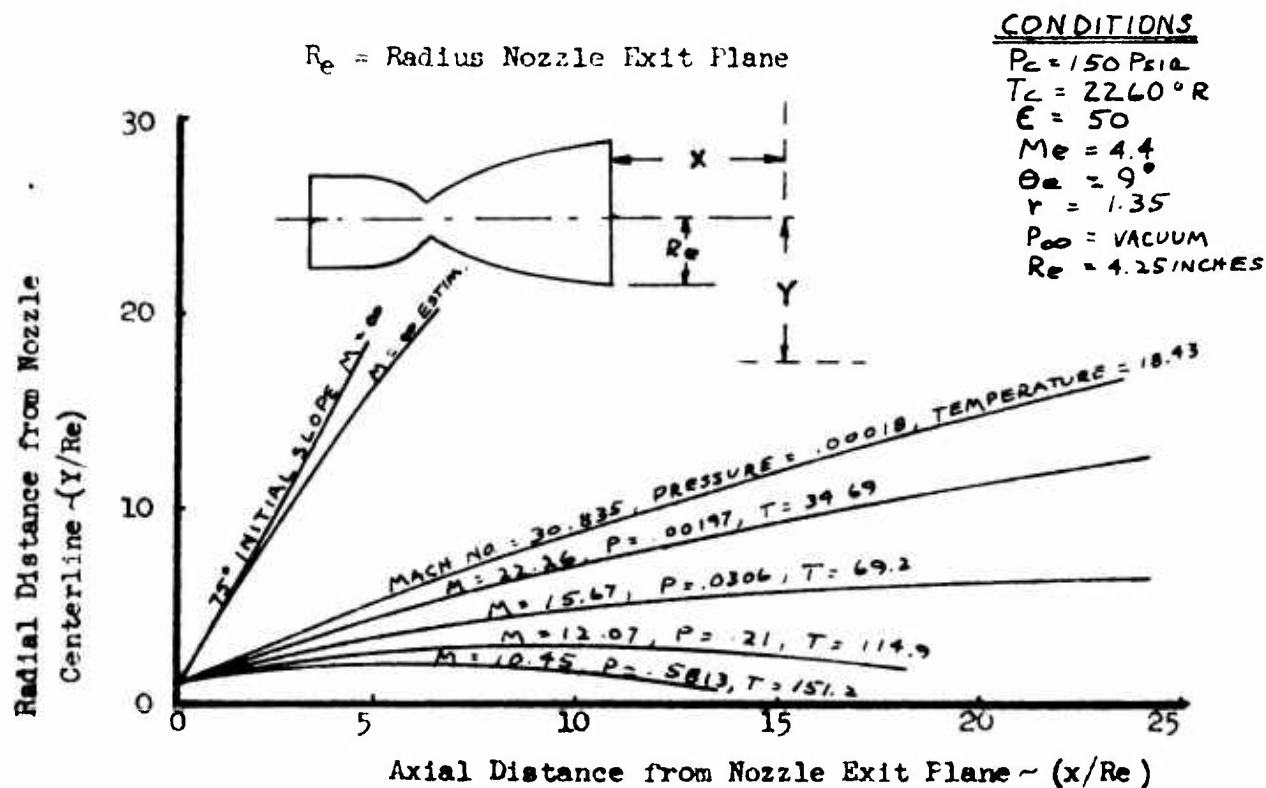


FIGURE 7.4-2 HYDRAZINE ENGINE EXHAUST PLUME (Ref. 32)

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Exhaust plume thermal radiation depends on plume size, temperature, and emissivity. Emissivity is especially significant in propellants having solid particles in the exhaust such as with hydrocarbon or aluminized fuels. Plume radiation from stored gases is not significant. With monopropellant engines it can be quite important though emissivity is rather low. Figure 7.4-2 shows the exhaust plume characteristics of a 200 lb. thrust hydrazine engine.

Heat conduction from the engine forward to the inlet plumbing and attach points will occur following shutdown and during certain pulsing duty cycles. This is referred to as heat "soakback" and is undesirable when it causes propellant boiling in the valve or valve inlet or if it induces larger conductive heat loads through attaching structure. Monopropellant engines, which have a high internal chamber mass, store a large amount of "resident heat" which can cause propellant detonation in the injector. These engines are usually designed to insure against post-operative heat soakback to the injector area by providing a thermal short to other areas such as the engine mounting flange.

7.5 LIFETIME

Propulsion system components are subject to life limitations measured by duration or number of cycles. Valves and regulators are primarily subject to cycle limits, usually in the range of thousands to millions of cycles. Propellant tank positive expulsion devices are limited to fewer cycles, possibly no more than one, such as with metallic diaphragms.

Rocket engines are both duration and cycle limited. Cold gas thrusters are sensitive to valve cycle limits. Heated gas thrusters are too, though they are also subjected to heater element lifetime limits. Figures 7.5-1 and 7.5-2 show estimated lifetime characteristics of tungsten wires and tubes

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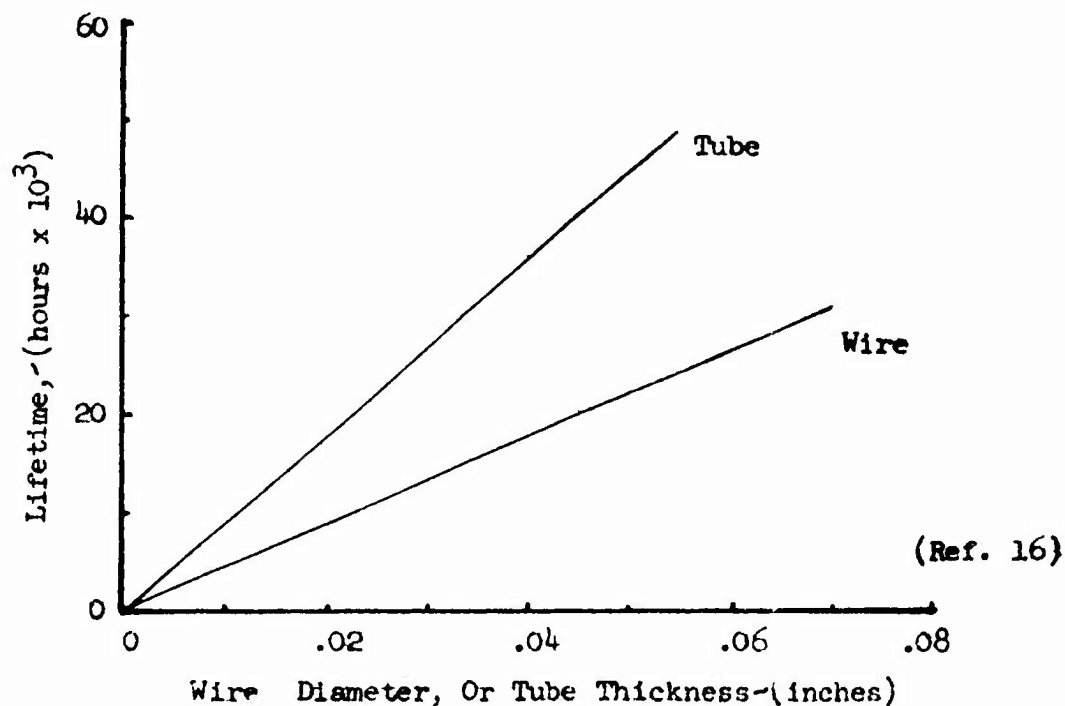


FIGURE 7.5-1 LIFETIME OF TUNGSTEN WIRES AND TUBES IN HYDROGEN

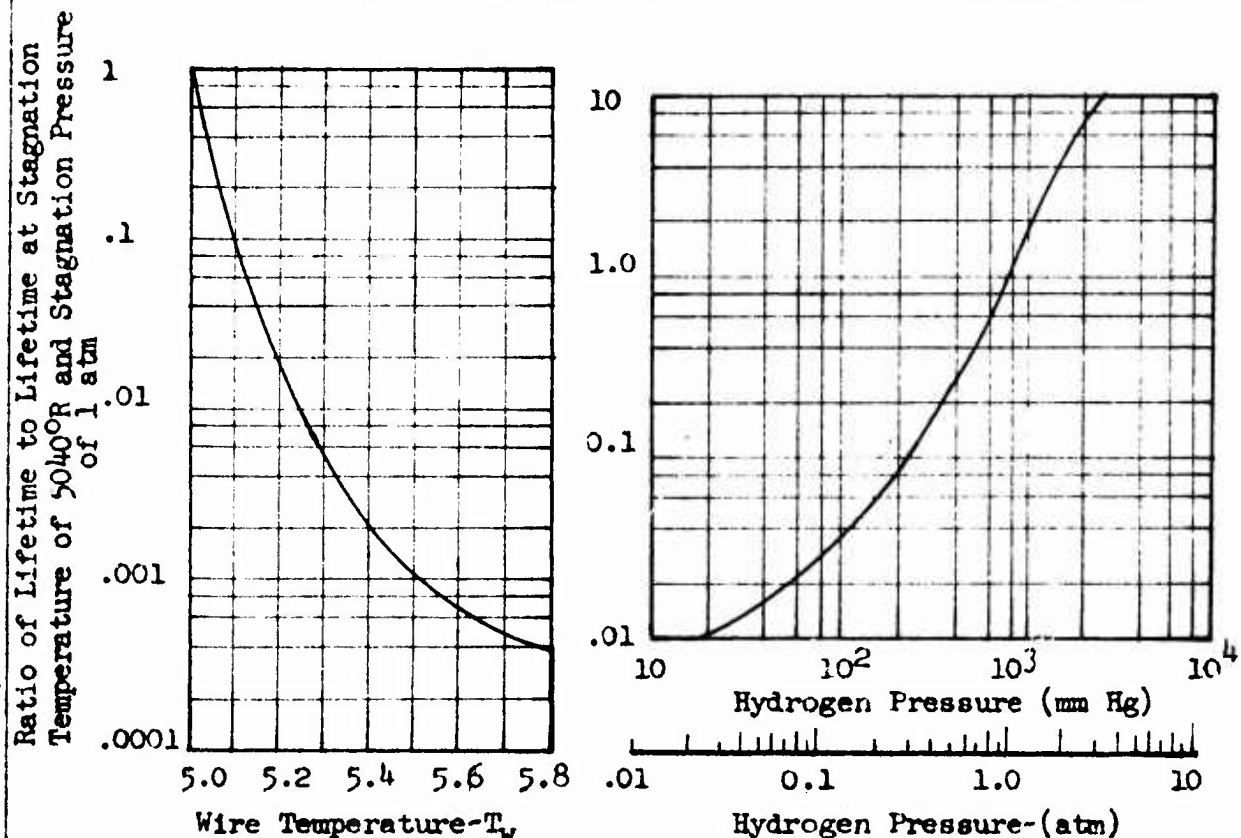


FIGURE 7.5-2 TEMPERATURE AND PRESSURE EFFECTS ON LIFETIME OF TUNGSTEN WIRES AND TUBES (Ref. 16)

in a hydrogen atmosphere. These characteristics are atmosphere dependent, but similar information for other gases was not generally available.

Monopropellant engines are also affected by the cycle limitations of liquid propellant valves, but their lifetime limits are usually discussed in terms of catalyst life. The destructive mechanism which affects catalyst life is erosion coupled with flexing and thermal cycling in wire screens and abrasion in particle catalysts. This is aggravated by extensive pulsing and high temperatures. Figure 7.5.3 shows catalyst life for various hydrogen peroxide thrusters in terms of thrust and operating duration. The lifetime characteristics of a hydrazine thruster using Shell 405 catalyst is shown in Figure 7.5-4 in terms of chamber pressure and propellant flow time. Lifetime of the non-spontaneous H-7 hydrazine catalyst is better than that of the Shell 405 "spontaneous" catalyst, but hydrazine and peroxide catalyst in general have more lifetime capability than is generally desired from small ΔV engines. Hydrazine monopropellant engines have now demonstrated over a million pulses, and over 8 hours of steady-state operation. Lifetime limits for monopropellant engine parts other than the valves and catalysts have not been identified in test or statistically established.

Bipropellant engine lifetime is primarily related to valve cycling and operating duration. The cycle limits of liquid propellant valves are more significant than with other engines since twice as many valves are involved. Ablative engines are life rated to operating duration for a particular duty cycle. Radiation and regeneratively cooled bipropellant engines have lifetime characteristics similar to monopropellant chambers. Their lifetime rating is usually stated as the qualification test requirement instead of the absolute

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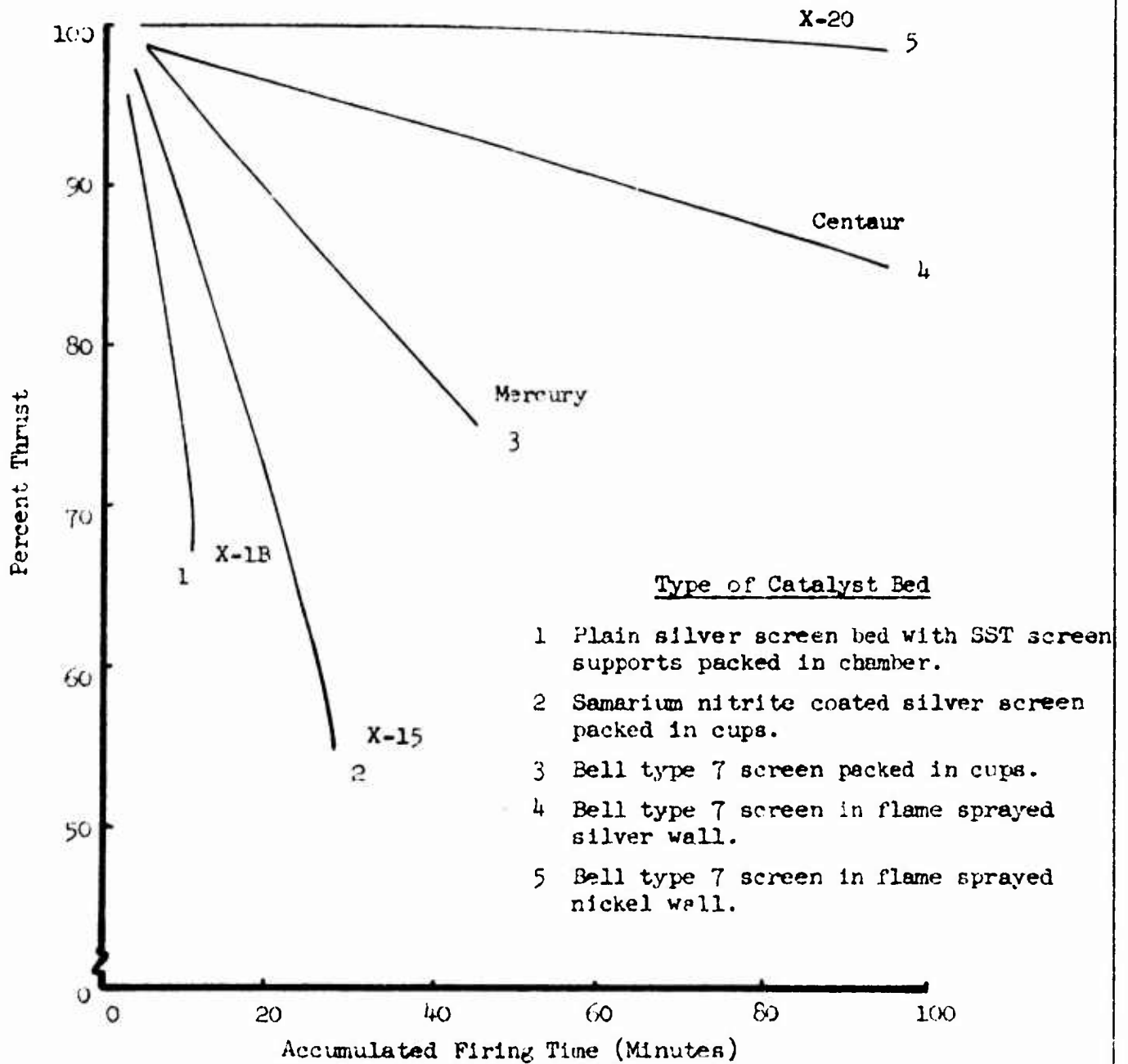


FIGURE 7.5-3 CATALYST BED LIFE-HYDROGEN PEROXIDE (Ref. 27)

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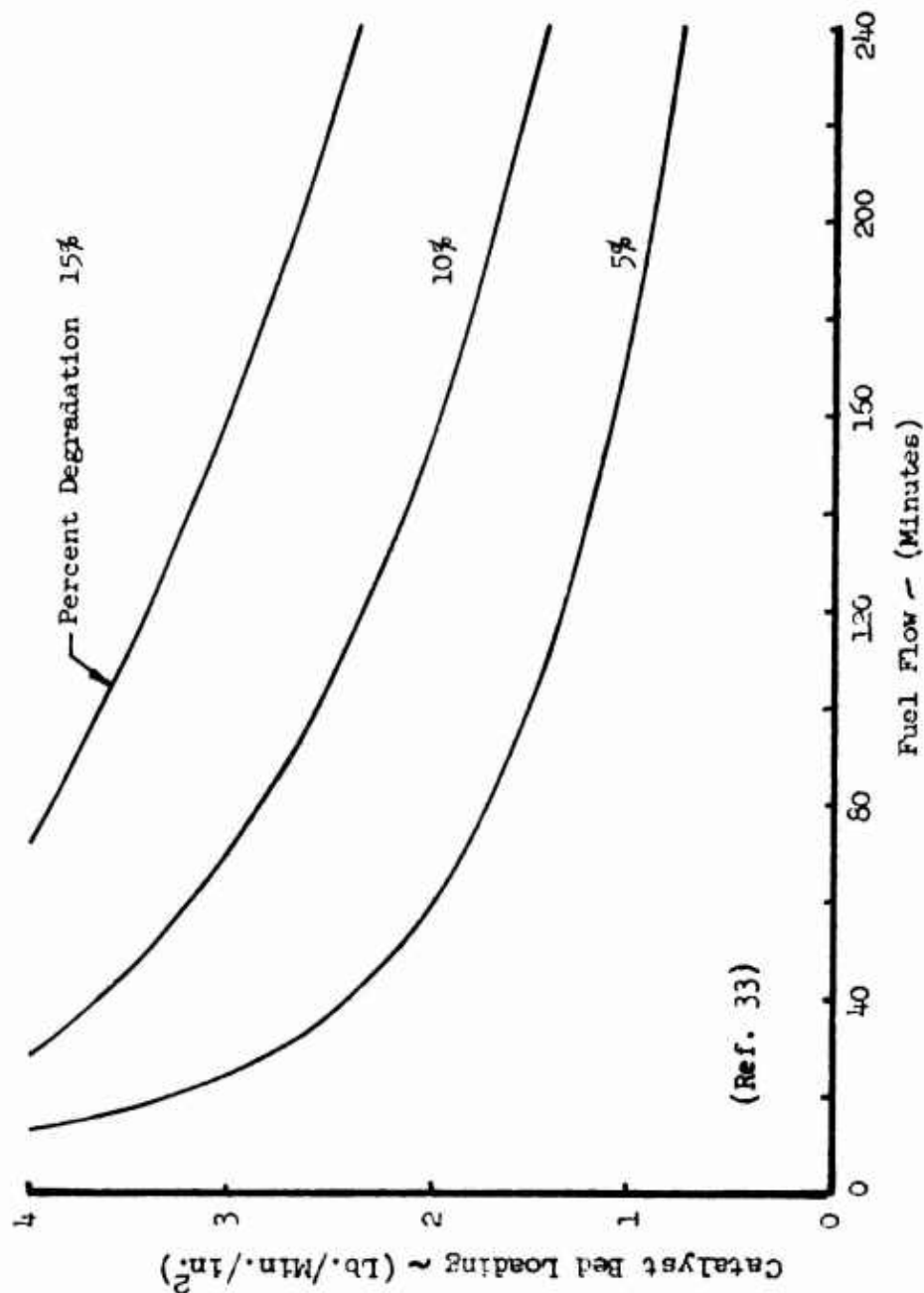


FIGURE 7.5-4 CATALYST BED LIFE CHARACTERISTIC - HYDRAZINE ENGINES

duration to failure since the latter requires more testing, and consequently cost, than is practical for most applications.

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